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CONTRACT NAS9-12068
DRL LINE ITEM 8

MSC 04483
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ORBITAL OPERATIONS STUDY

EXECUTIVE SUMMARY

FINAL REPORT

MAY 1972

APPROVED BY:

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TECHNICAL REPORT INDEX/ABSTRACT

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*MISSION MODELS, *ELEMENT PAIR INTERACTIONS, *ORBITAL INTERFACING ACTIVITIES, *EOS, *RAM, *MSS, *SPACE TUG

ABSTRACT

THIS DOCUMENT PRESENTS A SUMMARY OF THE ANALYSES OF THE ORBITAL OPERATIONS STUDY. OBJECTIVES, SCOPE OF STUDY, AND TECHNICAL DOCUMENTATION FORMAT ARE PRESENTED. A SUMMARY OF THE MISSION ANALYSES INCLUDING GENERIC MISSION MODELS, ELEMENT PAIR INTERACTIONS, AND INTERFACING ACTIVITIES ARE PRESENTED. THE ANALYSES ASSOCIATED WITH EACH INTERFACING ACTIVITY ARE ALSO SUMMARIZED. SIGNIFICANT IMPLICATIONS DERIVED DURING THE COURSE OF THE STUDY ON THE EOS ORBITER, SPACE TUG, RAM, AND MSS ARE INDICATED.

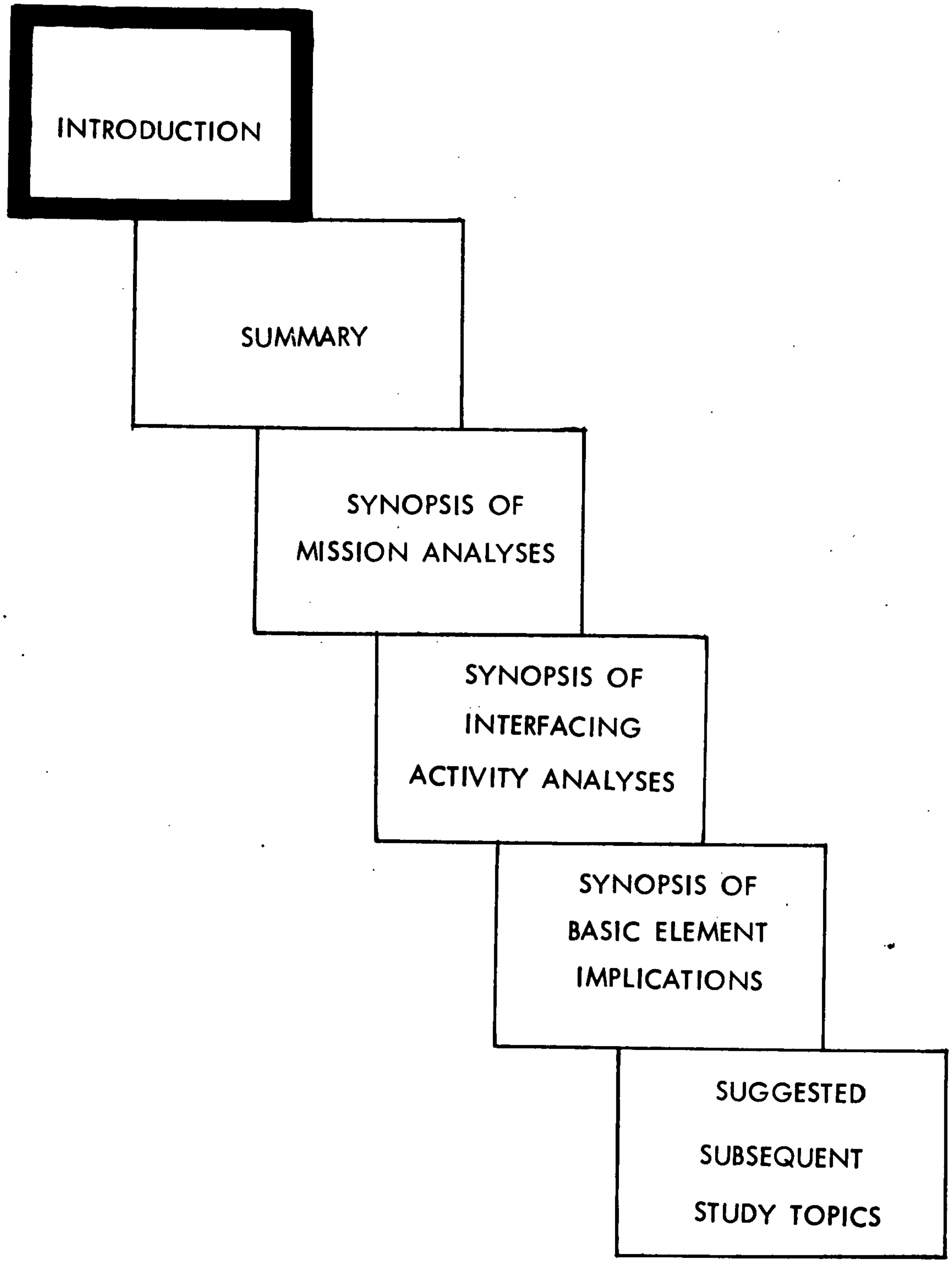
FOREWORD

This report presents a summary of the analyses conducted by North American Rockwell, Space Division under Contract NAS9-12068, Orbital Operations Study. It is submitted as partial fulfillment of contractual requirements and in accordance with line item 8 of the Data Requirements List (DRL 8).

CONTENTS

ILLUSTRATIONS

TABLES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1.0 INTRODUCTION

The space program has clearly evolved from the sequential, single mission approach of the Mercury-Gemini-Apollo programs to an era of simulataneous multiple missions involving many different space elements with unique objectives. A key ingredient in achieving the objectives of space exploration and exploitation of the late 1970's and 1980's is to develop systems that not only meet their individual primary requirements but also are flexible enough to satisfy continuously emerging requirements and new interfaces with future elements. An element-by-element or mission-by-mission customized approach will not be practical or economically feasible in the upcoming or next generation of space operations. The long life of reusable vehicles such as the space shuttle will require an integrated approach if these vehicles are to accommodate future space elements and operations without modifications and/or operational constraints.

OBJECTIVE

The diverse missions and design concepts that are contemplated for the next phase of space operations make it highly desirable, if not mandatory, to augment studies of specific elements with studies of a much broader scope; studies that transcend the unique requirements of an individual mission or element and foster commonality and compatibility of operational approaches.

This study, the Orbital Operations Study, was chartered to investigate one aspect of the operations discipline, earth orbital element pair interactions. The objectives of the study were:

1. Identify and analyze the potential earth orbital operational interactions between space elements.

2. Identify alternate approaches to the interactions and establish their safety and feasibility.

3. Synthesize representative procedures and design concepts for the alternate approaches.

4. Identify interrelated and synergistic design influences between elements and interfacing activities.

5. Develop a compendium of data that can be accessed as reference design specifications, guidelines, and/or recommendations for application to other similar orbital operations, space elements, or their associated subsystems.

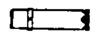
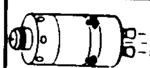
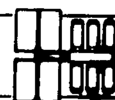
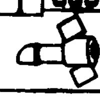
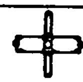
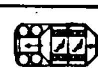
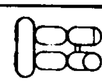
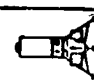
SCOPE

To be effective the study scope must be extremely broad. A long list of study ground rules would tend to stifle the identification of options and alternatives. Therefore, the only ground rules that were established for this study are:

1. Consider only earth orbital interacting operations.

2. Include a broad spectrum of vehicles, more specifically, the elements defined in Table 1-1.

Table 1-1. Inventory of Study Elements

<u>Earth orbital shuttle (EOS)</u> - One element only, referred to throughout this report as EOS, orbiter and shuttle orbiter.	
<u>Interim tug</u> - Various types of nonreusable nonreturnable, and nonreusable returnable kick stages such as Centaur, Agena, Titan Transtage, and Burner II.	
<u>Space tug</u> - Reusable unmanned and manned ground-based tug, and unmanned and manned space-based tug.	
<u>Chemical propulsion stage (CPS)</u> - The orbital insertion stage (mounted on the EOS booster at launch), the earth orbit-to-orbit shuttle, and the cislunar shuttle. The CPS can be modular or nonmodular, and single-stage or two-stage.	
<u>Reusable nuclear shuttle (RNS)</u> - Both the earth orbit-to-orbit shuttle and the cislunar shuttle application. The RNS can be modular or nonmodular and is single-stage only.	
<u>Modular space station (MSS)</u> - The low earth orbital station and the geosynchronous station.	
<u>Research and applications module (RAM)</u> - Both attached and detached RAM's, supported by the EOS and by either of the two MSS's (see above).	
<u>Satellite</u> - Satellites deliverable to orbit by the EOS and those requiring the EOS plus a third stage for delivery. Also included are satellites requiring retrieval and servicing.	
<u>Orbital propellant depot (OPD)</u> - The low earth orbital propellant depot located in an orbit optimized to support the RNS or CPS and the space-based tug.	
<u>Earth orbital resupply module</u> - Cargo and propellant modules for resupply of earth orbiting elements.	
<u>Orbiting lunar station (OLS)</u> - Both the modular and nonmodular configurations (deliverable to lunar orbit by CPS or RNS).	
<u>Lunar surface base (LSB)</u> - The modular base only (deliverable to lunar orbit by CPS or RNS).	
<u>Lunar landing tug (LLT)</u> - Both the unmanned and manned tugs (deliverable to lunar orbit by CPS or RNS).	
<u>Lunar resupply module</u> - Crew, cargo and propellant modules for delivery to lunar orbit by CPS or RNS.	

The first ground rule was intended to exclude prelaunch, launch, deep space, entry, landing, and post-landing operations. Ground support of on-orbit operations was included in the study as part of the alternate approaches. The assumed capabilities of the data flow network are illustrated in Figure 1-1. Both the postulated Ground Network, and the Tracking and Data Relay Satellite system concepts are depicted in the figure.

The second ground rule was intended to include a broad spectrum of elements that would be representative through the 1980's. This inventory includes both modular and non-modular configurations of several elements, multiple tug configurations (manned/unmanned, space based/ground based), Research and Application Modules (RAM's), habitable and non-habitable modules, and unmanned free-flying modules. Large mass elements representative of future programs are also included (e.g., RNS, CPS, OPD, etc.).

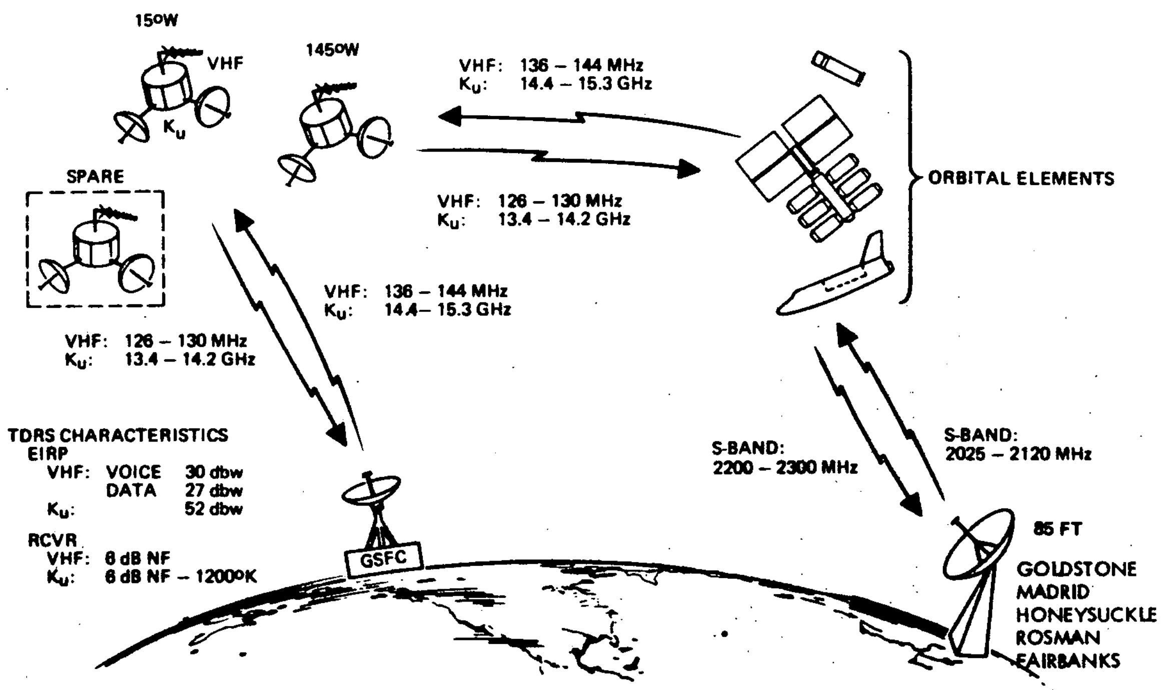
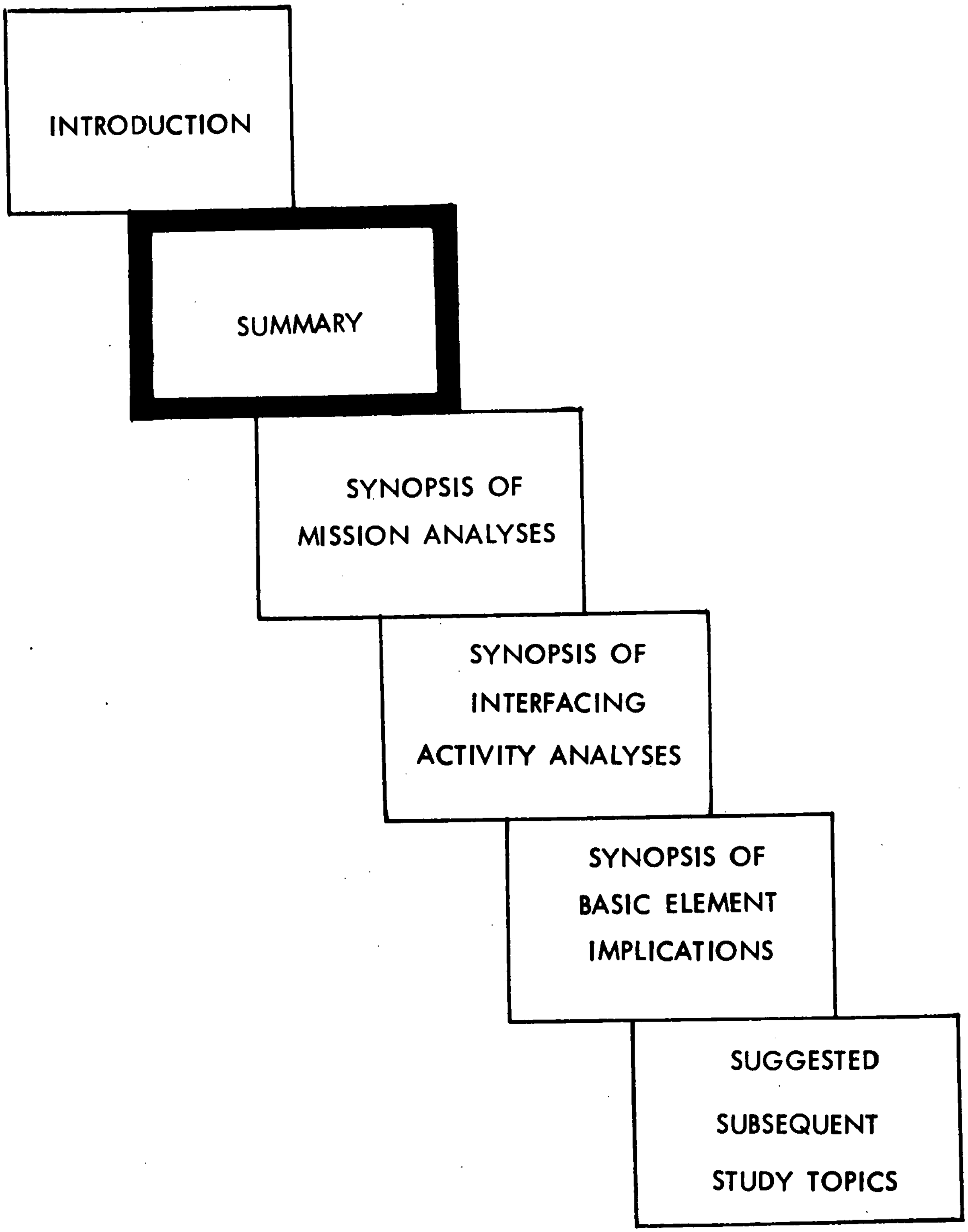


Figure 1-1. Ground Network and TDRS Models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2.0 SUMMARY

This executive summary document is presented in two levels of detail with references to the technical report of the Orbital Operations Study for in-depth analysis data. This section (2.0) presents a very condensed study overview and summary of major study results. Sections 3.0, 4.0, 5.0, and 6.0 of this report present a more detailed synopsis of the study results.

STUDY OVERVIEW

Figure 2-1 illustrates not only the format and interrelationship of the detailed technical reports of the study, but also the study logic that was used and the principal products of the study.

The initial task of the study resulted in the synthesis of representative mission models that identified all potential element pair interactions. Interfacing activities that could occur during the element pair interactions were defined. As noted on Figure 2-1 this task was documented in Volume I of the technical report.

The second major task consisted of the analyses of the interfacing activities to examine potential approaches for their accomplishment and to identify the implications thereof. This primarily was intended to assure that safe, feasible methods would be available to accomplish each interfacing activity. It was also intended to identify the requirements and design influences associated with each approach. Based upon the integrated space program postulated for the 1980's, preferred appraoches--with supporting rationale--were also selected to indicate study conclusions.

The interfacing activity analyses were reported in Volume II as four separate books for the convenience of the potential users. Figure 2-2 illustrates the interrelationship of the books. Part 1 presents an overview of all the activity analyses; Part 2 includes those activities that are primarily associated with the structural and mechanical design disciplines; Part 3 is a compilation of the activity analyses that primarily relate to data management functions; Part 4 presents the analyses associated with on-orbit support operations.

Study results that pertain specifically to the EOS, Tug, RAM, and MSS were extracted from Volumes I and II and compiled separately in Volume III of the technical report.

Comprehensive trade studies that were conducted in support of the interfacing activity analyses were only summarized in Volume II. The detailed trade study data are contained in Appendix A.

Operational procedures, which were developed to identify detailed functional requirements and validate the alternate approaches, are summarized

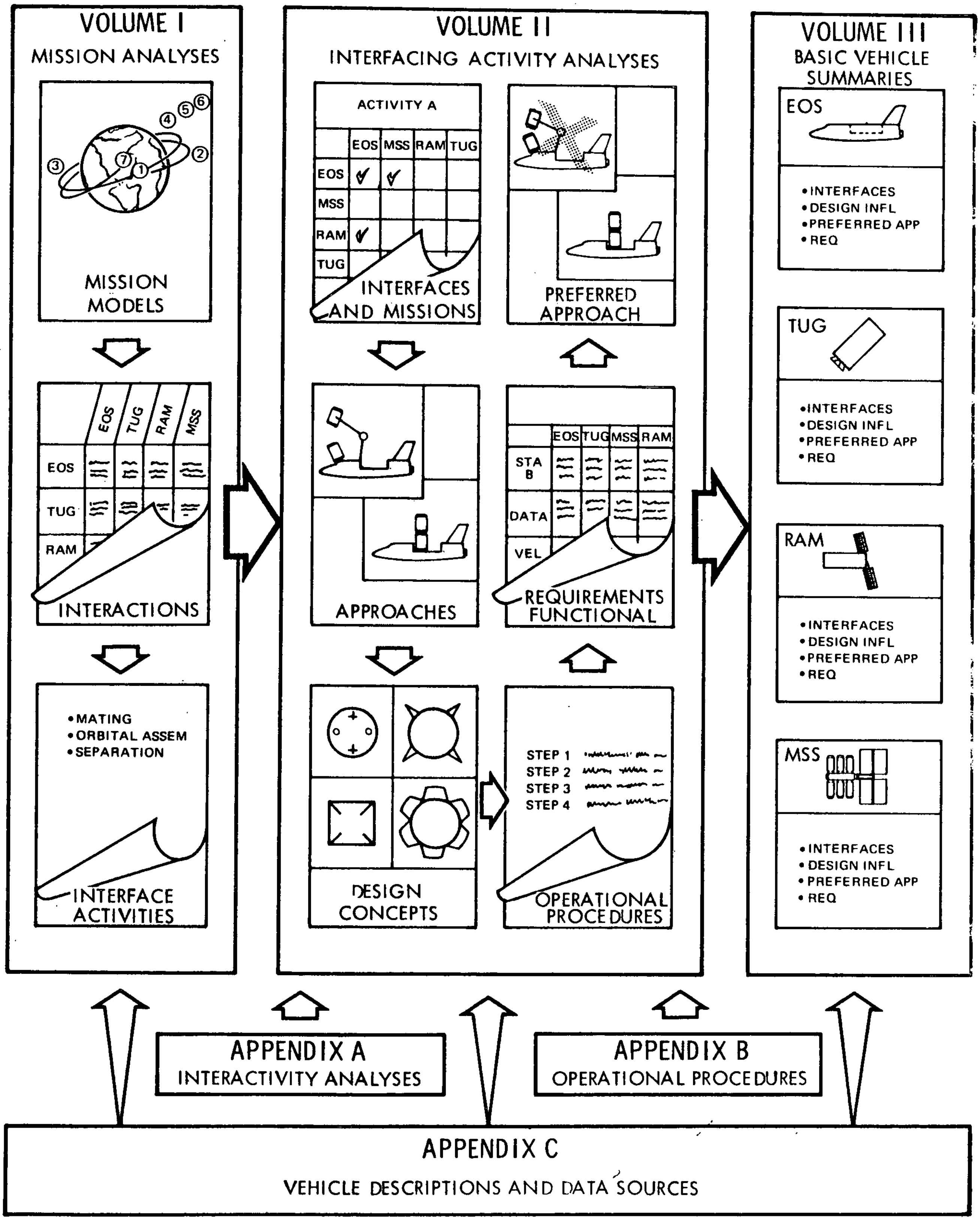


Figure 2-1. Data Package Report Grouping

in Volume II. The step-by-step sequence of events for all the procedures are presented in Appendix B.

Gross descriptions of the elements included in the analyses of the study are presented in Appendix C. Also a bibliography of the documents utilized throughout the study is included in Appendix C.

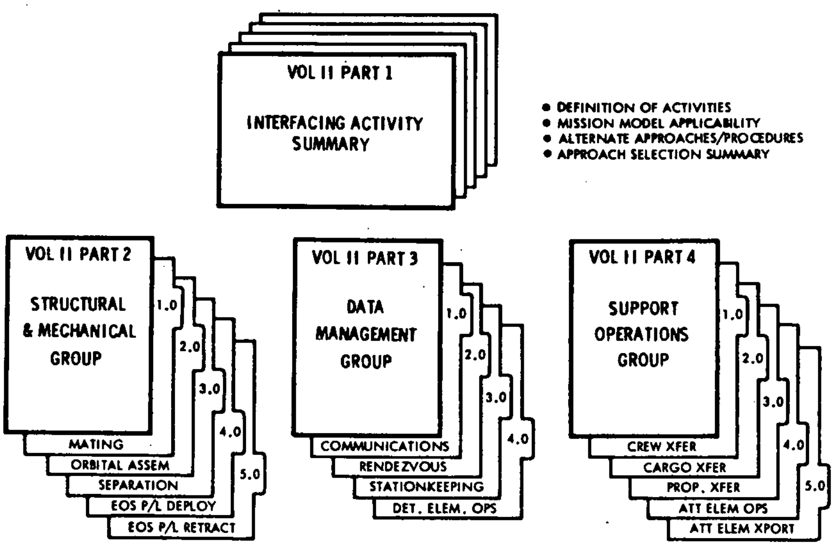


Figure 2-2. Volume II Organization

MISSION ANALYSES CONDENSED SUMMARY

Section 3 of this report presents the major results of the mission analyses. Approximately 40 design reference missions that were developed during studies of a single element were anlayzed. Integration of these missions, based upon potential applications and capabilities of the elements involved, resulted in the establishment of 11 representative mission models (Table 2-1).

Table 2-1. Representative Mission Models

VEHICLE	MISSION MODELS		INTERFACING ELEMENTS
EARTH ORBITAL SHUTTLE	MM-1	EMPLACEMENT	RAM; SATELLITE; KICKSTAGE; TUG; FIRST MOD OF MSS, OLS, OPD, CLS
	MM-2	LOGISTICS/RETRIEVAL	MSS; CLS; OLS; RAM; TUG; SATELLITE; EOS; OPD; CARGO, PROPELLANT, LSB MODS
	MM-3	SORTIE	RAM
SPACE BASED TUG	MM-4	RETRIEVAL/EMPLACEMENT	RAM; SATELLITE; CLS; TUG; OPD; EOS; MSS; OLS; OIS
	MM-5	LOGISTICS	LLT; RAM; SAT; MSS; CLS; TUG; EOS; OPD; CARGO MODS
	MM-6	DISPOSAL	CLS; OIS; OPD; MSS; OPD
GROUND BASED TUG	MM-7	EMPLACEMENT/SORTIE	TUG; SAT; RAM
	MM-8	LOGISTICS/RETRIEVAL	TUG; CLS; SAT; MSS; RAM; OPD; EOS; PROPEL, CARGO MODS
OIS	MM-9	DELIVERY	CLS; OLS; OPD; TUG
CISLUNAR SHUTTLE	MM-10	STAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS
	MM-11	NONSTAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS

There were 117 element pair interactions identified from the 11 representative missions. Fourteen interfacing activities were defined to scope the operations that could occur in an element pair interaction. Table 2-2 presents the definition of these activities. Each of the 117 element pair interactions were analyzed to determine which interfacing activities were applicable to each interaction. Figure 2-3 illustrates the potential number of activity-element pair combinations.

Table 2-2. Interfacing Activity Definition

MATING	ATTACHMENT OF TWO ELEMENTS/MODULES
ORBITAL ASSEMBLY	ATTACHMENT INVOLVING THREE OR MORE ELEMENTS/MODULES
SEPARATION	DEMATING OF ELEMENTS/MODULES
EOS PAYLOAD DEPLOYMENT	EXTENSION/REMOVAL OF PAYLOADS FROM THE CARGO BAY
EOS PAYLOAD RETRACTION & STOWAGE	INSERTION/ATTACHMENT OF PAYLOADS INTO THE CARGO BAY
COMMUNICATIONS	TRANSFER OF INFORMATION VIA SPACE LINKS
RENDEZVOUS	ESTABLISHMENT OF ELEMENT PAIR ORBITAL RELATIONSHIP
STATIONKEEPING	MAINTENANCE OF AN ELEMENT PAIR ORBITAL RELATIONSHIP
DETACHED ELEMENT OPERATIONS	SUPPORT OF FREE-FLYING ELEMENTS
CREW TRANSFER	TRANSFER OF PERSONNEL BETWEEN ELEMENTS
CARGO TRANSFER	INTERCHANGE OF PACKAGED AND FLUID CARGO BETWEEN ELEMENTS
PROPELLANT TRANSFER	RESUPPLY OF LARGE QUANTITIES OF LIQUID PROPELLANTS
ATTACHED ELEMENT OPERATIONS	SUPPORT FROM ONE ELEMENT TO AN ATTACHED ELEMENT
ATTACHED ELEMENT TRANSPORT	LOGISTICS ELEMENT SUPPORT TO A PAYLOAD DURING TRANSPORT

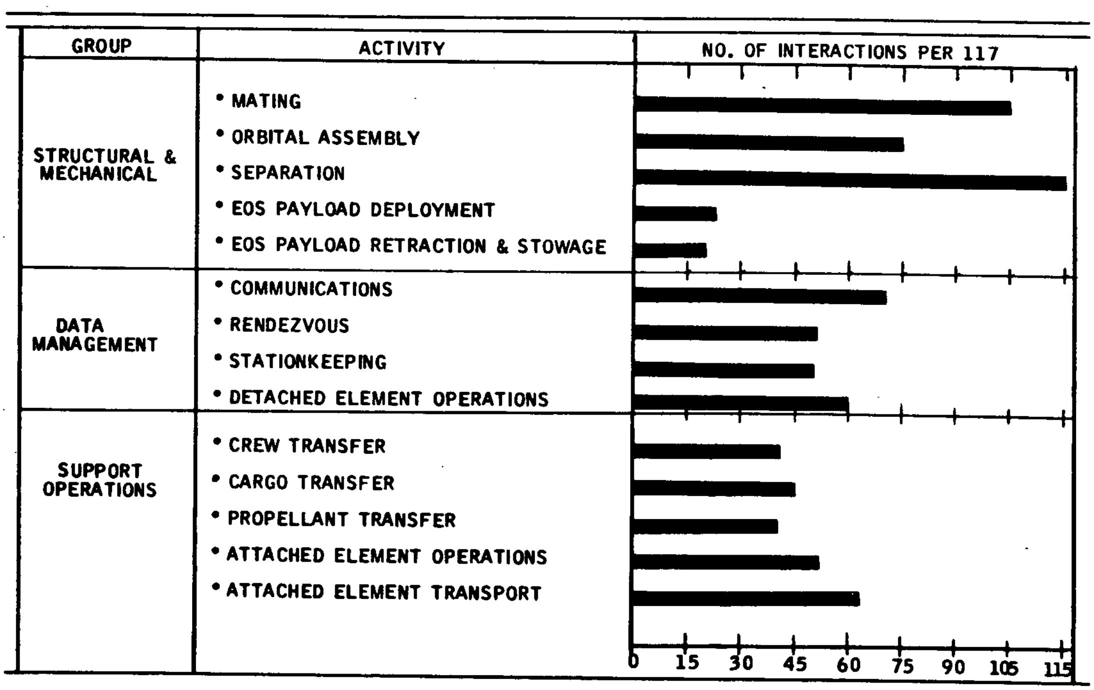


Figure 2-3. Potential Element Pair Operational Interfaces

INTERFACING ACTIVITY ANALYSES CONDENSED SUMMARY

A synopsis of the results of the interfacing activity analyses contained in Volume II of the technical report is presented in Section 4.0 of this report. A condensed summary of the major results is presented below.

Structural Mechanical Group

The alternate approaches evaluated for the structural-mechanical group of interfacing activities are illustrated in Figure 2-4. The preferred approaches for each activity are listed in Table 2-3. Table 2-4 lists the significant design influences/hardware complements that result from the selections. Note that both the primary and secondary drivers for the recommendations are indicated.

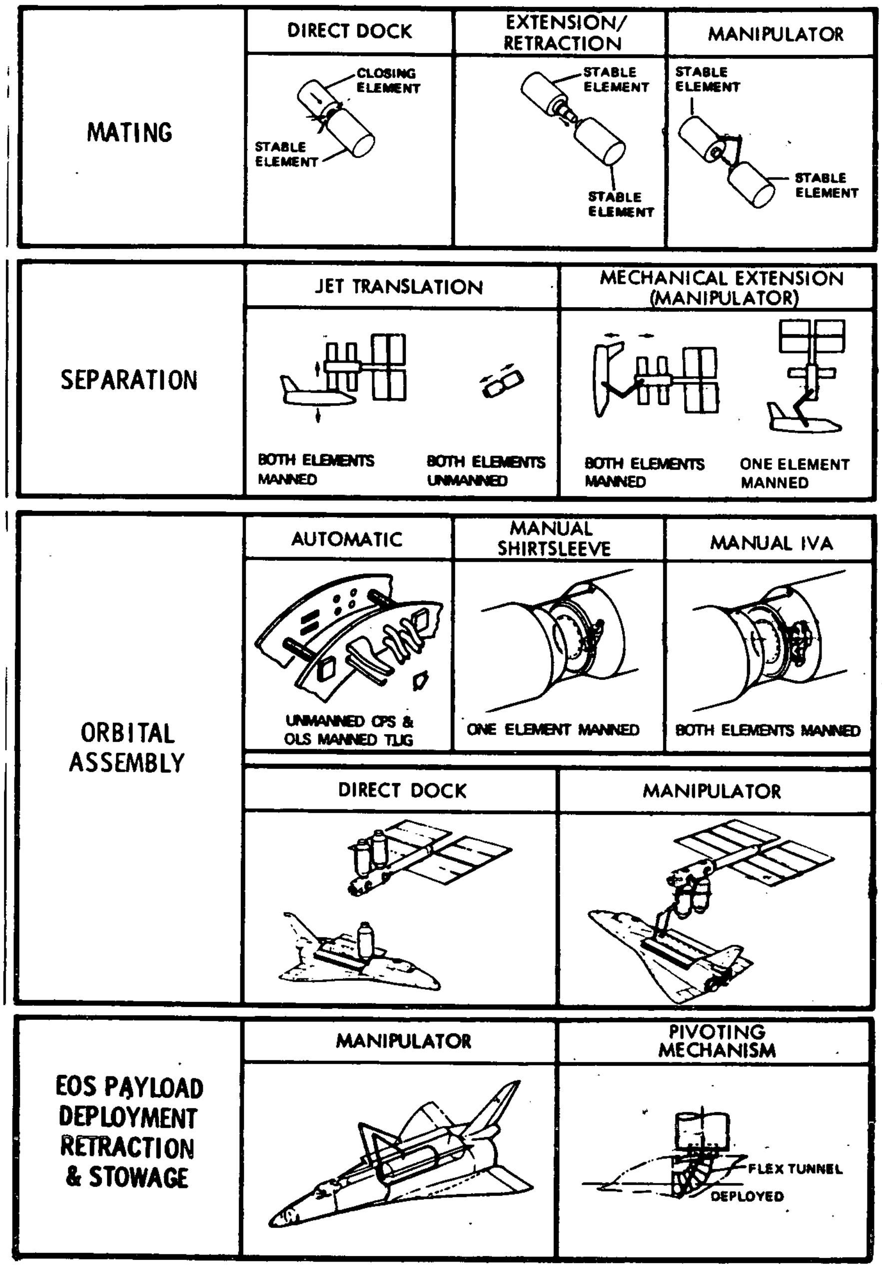


Figure 2-4. Structural-Mechanical Group Alternate Approaches

Table 2-3. Structural-Mechanical Group Preferred Approaches

Interfacing Activity	Preferred Approach
Mating	DIRECT DOCK - Standardized docking port feasible for all elements except small satellites; adapter for mating between satellites and logistics elements
Orbital Assembly	DIRECT DOCK - Applicable to CPS, RNS, OPD and cislunar payloads. MANIPULATOR - Preferred for MSS assembly
Separation	JET TRANSLATION - Choice of propellants and jet location, significant design considerations
EOS Payload Deployment and Retraction	PIVOTAL MECHANISM - Preferred for single payloads and attached RAM operations MANIPULATOR - Preferred for handling of multiple payloads

Table 2-4. Structural-Mechanical Group Recommendation

DESIGN INFLUENCES	DRIVERS	
	PRIMARY	SECONDARY
DIRECT DOCK • 100-400 FT-LB ATTENUATION • ≤ 0.4 FT/SEC CLOSING VELOCITY • COMMON MATING PORT	MATING	ORBITAL ASSEMBLY SEPARATION
AUTOMATED DOCKING/UNDOCKING • LASER RADAR • PASSIVE REFLECTORS • TV (UNMANNED-TO-UNMANNED)	MATING SEPARATION STATIONKEEPING	RENDEZVOUS
PAYLOAD HANDLING • PIVOTAL MECHANISM (EOS Only) • MANIPULATOR (EOS ONLY)	MATING EOS P/L DEPLOY ORBITAL ASSY.	EOS P/L RETRACT & STOWAGE
EOS PAYLOAD RETENTION • 4-POINT COPLANAR • KIT CLAMP OR HINGE (SELECTED PAYLOADS)	EOS P/L RETRACT	ATTACHED ELEM TRANSPORT
PAYLOAD EGRESS • EOS AIRLOCK KIT	EOS P/L DEPLOY/ RETRACT AND STOWAGE	CREW TRANSFER CARGO TRANSFER
SATELLITE CAPTURE • SIMPLE MANIPULATION (EXTENSION/RETRACTION)	MATING	CARGO TRANSFER

Data Management Group

The alternate approaches that were evaluated for the data management group of interfacing activities are illustrated in Figure 2-5. The preferred approaches for each activity are listed in Table 2-5. Table 2-6 lists the design influence/hardware complements that result from the selections.

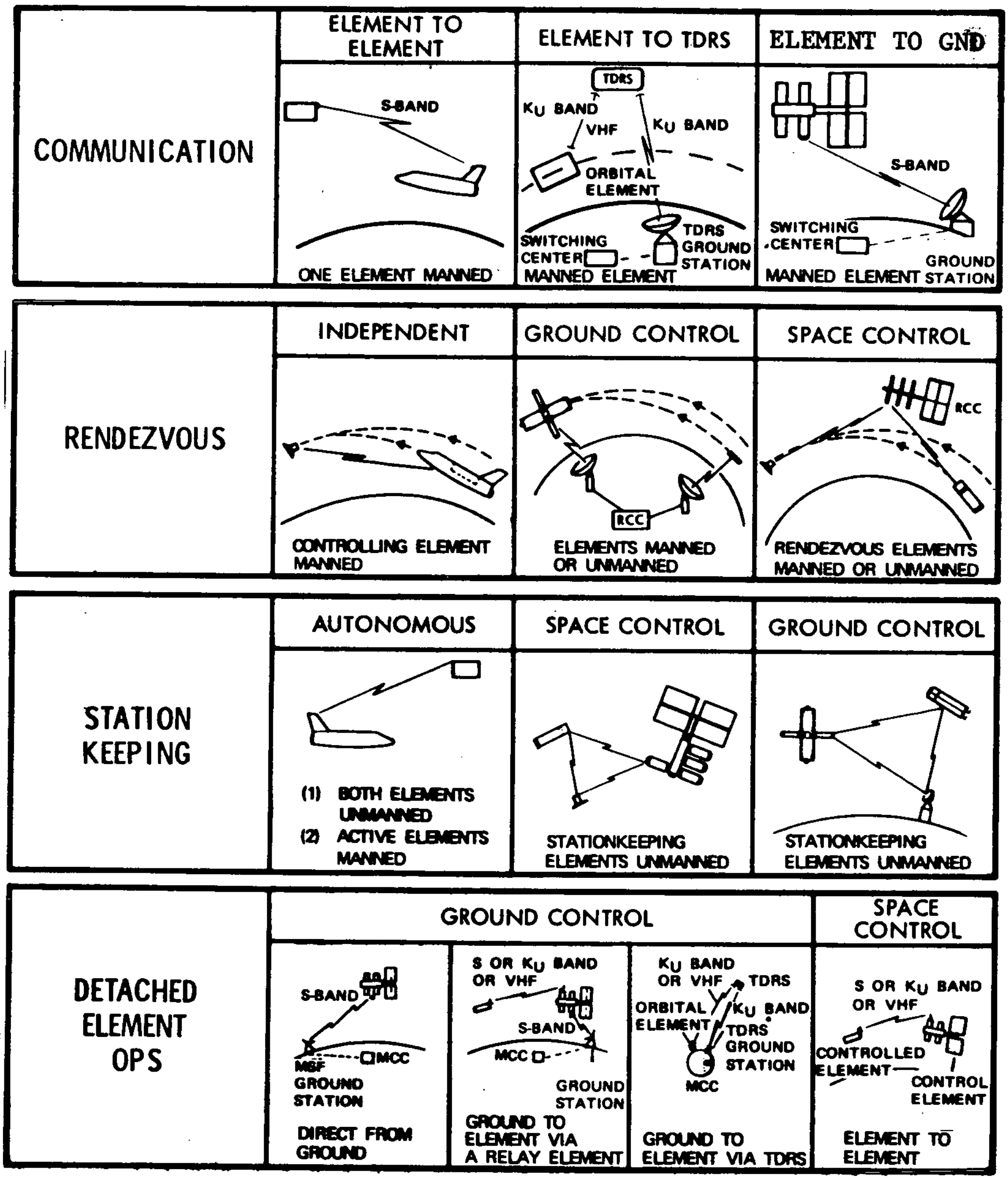


Figure 2-5. Data Management Group Alternate Approaches

Table 2-5. Data Management Group Preferred Approaches

Interfacing Activity	Preferred Approach
Communications	ELEMENT TO ELEMENT - S-band primary and VHF backup on all elements; Ku-band for MSS-RAM links ELEMENT TO TDRS - Ku-band on MSS and selected RAMs and satellites ELEMENT TO GROUND NETWORK - S-band primary and VHF backup on all elements
Rendezvous	INDEPENDENT - All manned logistics elements; selected unmanned tugs; terminal phase for all elements GROUND CONTROL - At long ranges for unmanned elements. Update and monitor for manned elements SPACE CONTROL - Only MSS-tug-RAM operations
Stationkeeping	AUTONOMOUS - All close proximity operations GROUND CONTROL - All long-range operations except for MSS operations SPACE CONTROL - MSS operations
Detached Element Operations	GROUND OPERATIONS - Direct to ground Data rates < 1Mbps, ground network Data rates > 1Mbps, TDRS SPACE OPERATIONS - MSS-RAM-tug operations only

Table 2-6. Data Management Group Recommendations

DESIGN INFLUENCES	DRIVERS	
	PRIMARY	SECONDARY
SCANNING LASER RADAR • RANGE & RANGE RATE } EOS, MANNED TUG, MSS PASSIVE REFLECTORS • ALL ELEMENTS	RENDEZVOUS STATIONKEEPING	MATING
SPACE CONTROL • ON-BOARD DATA PROCESSING - MSS ONLY • 3 ELEMENTS IN CONJUNCTION - MSS WITH TUG & RAM	RENDEZVOUS STATIONKEEPING	DETACHED ELEM OPERATIONS
INDEPENDENT CONTROL • HORIZON SCANNERS • IMU • STAR TRACKERS } EOS, MSS, TUG (SELECTED MISSIONS)	RENDEZVOUS STATIONKEEPING	DETACHED ELEM OPERATIONS
GROUND CONTROL • >75 N MI - ALL ACTIVE ELEMENTS	RENDEZVOUS STATIONKEEPING	
S-BAND • OMNI ANTENNA • 1 MBPS ALL ELEMENTS	COMMUNICATIONS DET. ELEM. OPS.	ATTACHED ELEM OPERATIONS
Ku-BAND • DIRECTIONAL ANTENNA • 10 MBPS • VHF ORDER WIRE } MSS SELECTED RAM's, SAT	COMMUNICATIONS DET. ELEM. OPS.	ATTACHED ELEM OPERATIONS

Support Operations Group

The alternate approaches for the support operations group of interfacing activities are illustrated in Figure 2-6. The preferred approaches for each activity are listed in Table 2-7. Table 2-8 lists the design influences/ hardware complements that result from the selections.

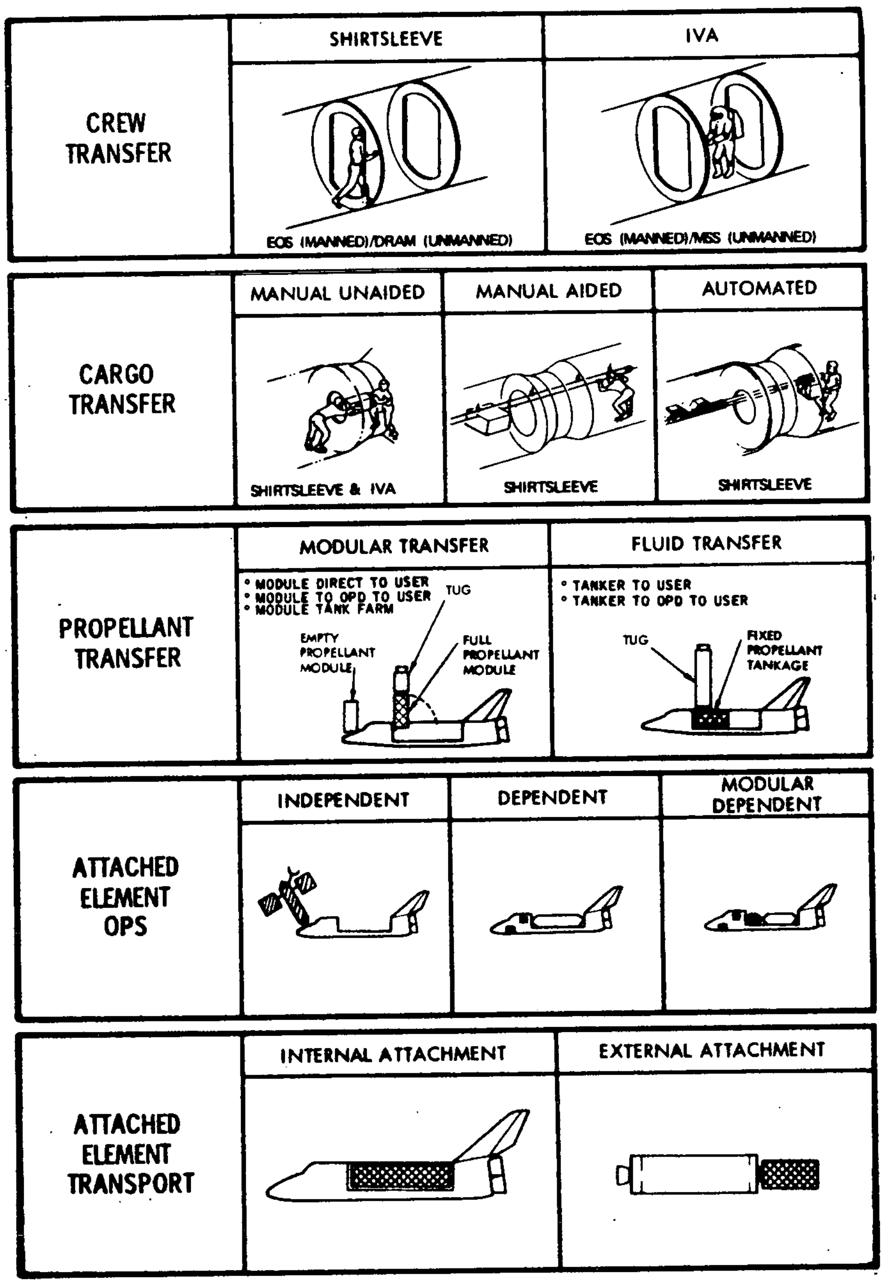


Figure 2-6. Support Operations Group Alternate Approaches

Table 2-7. Support Operations Group Preferred Approaches

Interfacing Activity	Preferred Approach
Crew Transfer	SHIRTSLEEVE - All ground crew rotation between elements IVA - Required operations, non-mannable elements
Cargo Transfer	PACKAGE CARGO MANUALLY UNAIDED - All interfaces except those involving an earth orbit resupply module and satellites MANUALLY AIDED - MSS, CPS, RNS, OPD, and RAM with a resupply module AUTOMATIC - Satellite FLUID TRANSFER MANUAL PLUMBED - All interfaces that are accessible to either shirtsleeve or IVA mode AUTOMATIC - Inaccessible interfaces
Propellant Transfer	FLUID TRANSFER - Direct from logistics propellant module
Attached Element Operations	INDEPENDENT - Unique RAM support requirements (e.g., astronomy module stability) DEPENDENT - RAMs and tugs associated with MSS; RAM access only to EOS available capability MODULAR DEPENDENT - Add-on or kit installations on the EOS (e.g., airlock, RAM support module)
Attached Element Transport	INTERNAL - EOS load distribution requirements set by launch and entry EXTERNAL - Current docking port concepts adequate for axial loads; multiple payloads on CPS/RNS require special adapter

Table 2-8. Support Operations Group Recommendations

DESIGN INFLUENCES	DRIVERS	
	PRIMARY	SECONDARY
SHIRTSLEEVE CREW AND CARGO TRANSFER • 41-IN. DIA HATCH • MONITOR ATMOSPHERE • VIEW INTERIOR } ALL EXCEPT NON-MANNABLE ELEM'S: • SAT MANIPULATION • EOS AIRLOCK KIT	CREW TRANSFER CARGO TRANSFER	ATTACHED ELEM OPERATIONS MATING EOS PAYLOAD DEPLOY & RETRACT
MANUAL PLUMBED FLUID TRANSFER (SMALL) • 48-IN. DIA CREW WORK SPACE - ALL EXCEPT SAT & UNMANNED TUG: AUTOMATIC FLUID TRANSFER	CARGO TRANSFER	—
DIRECT FLUID TRANSFER (LARGE) • RESUPPLY TANK • LINEAR ACCELERATION • STATIONKEEPING EOS } IN PLANE BURN • NO TRANSPORT TUG • NO OPD	PROPELLENT XFER	STATIONKEEPING
RAM SUPPORT (ATTACHED) • LIMITED - EOS • ALL INCLUSIVE - MSS	ATTACH. ELEMENT OPERATIONS	COMMUNICATIONS DETACHED ELEM OPERATIONS

CONDENSED BASIC ELEMENT SUMMARIES

Section 5.0 of this report presents a synopsis of the study results applicable to four basic elements: (1) EOS, (2) Tug, (3) RAM, and (4) MSS. A condensed summary is presented below. Volume III of the technical report contains additional background and the details of the analyses applicable specifically to these four elements.

Earth Orbital Station (EOS)

Figure 2-7 illustrates the conclusions that pertain to the EOS. Both the pivotal mechanism and the manipulator are recommended for inclusion on the EOS for payload handling. An airlock is also identified but is not required as a basic provision of the EOS for element pair operations. It can be a kit installation. Both S-band and VHF are recommended for inclusion in the EOS. S-band fulfills the basic requirements; VHF is recommended as the alternate or redundant communications link. It is recommended that on-orbit support to attached payloads be limited to access to the available basic capabilities of the EOS.

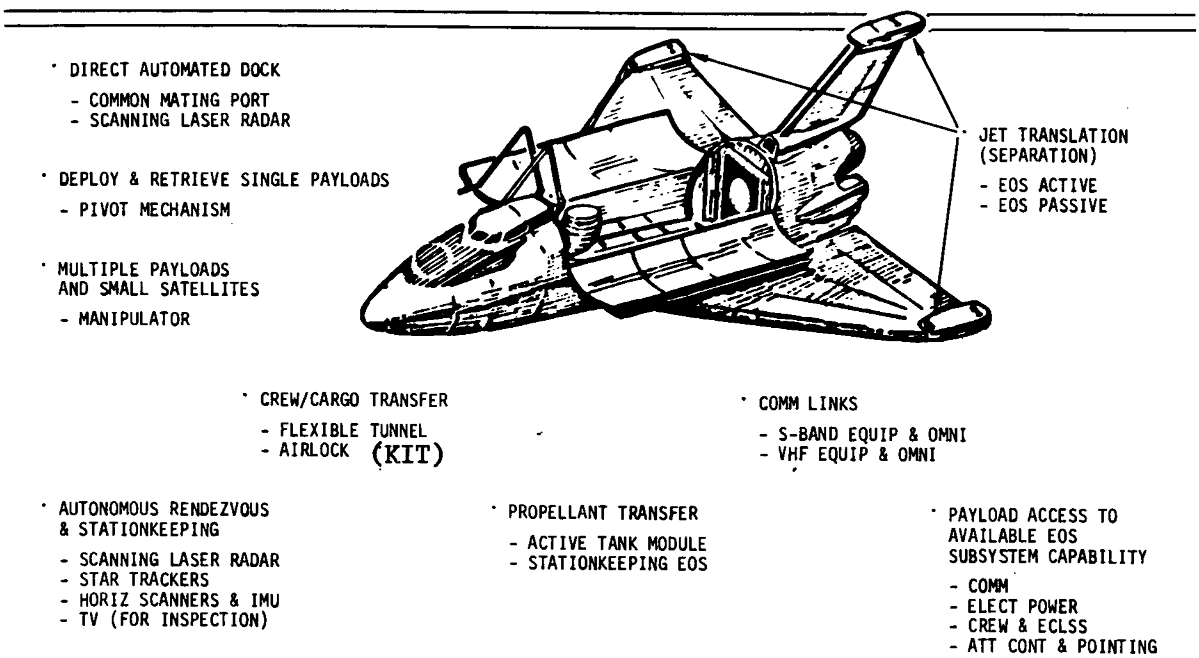
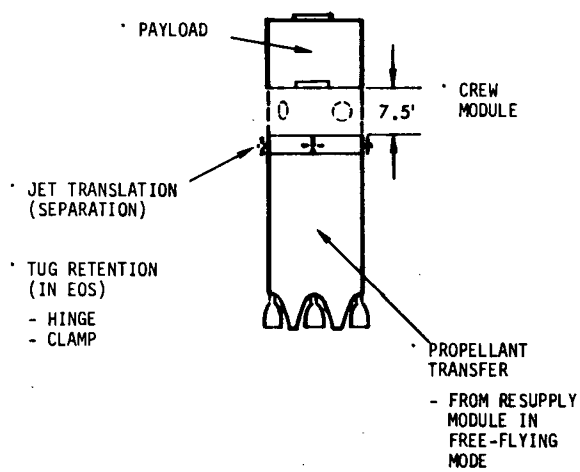


Figure 2-7. Summary of EOS Recommendations

Tug

Figure 2-8 illustrates the conclusions of the study that pertain to the tug. Direct automatic dock is the preferred mating concept. A laser scanning radar is recommended to assist in the mating operation, especially in the case of mating of an unmanned tug to another unmanned element. An adapter will be required for mating between a "standard" docking port on the tug and small satellites. Some of the proposed tug configurations will require a unique retention concept for delivery by the EOS. Detailed design trades on this particular interface must be conducted in subsequent studies on these two elements. S-band is the preferred communications link, but VHF is recommended as the alternate or redundant technique. The recommended concept for on-orbit propellant resupply to the tug is by means of fluid transfer directly from a logistics tank. The transfer is accomplished during free-flying operations of the tug and the attached propellant module.

- DIRECT AUTOMATED DOCK
  - COMMON MATING PORT
  - SCANNING LASER RADAR



- SATELLITE MATING
  - EXTENSION/RETRACTION DEVICE
- CREW & CARGO TRANSFER
  - CARGO - MANUALLY UNAIDED
  - CREW - SHIRTSLEEVE
- COMM LINKS
  - VHF OMNI
  - S-BAND OMNI
- AUTONOUOUS RENDEZVOUS & STATIONKEEPING
  - GROUND CONTROL OF RENDEZVOUS TO WITHIN 50 NAUTICAL MILES
  - LASER SCANNING RADAR
  - TV
  - HORIZ SCANNER & IMU
  - STAR TRACKER

Figure 2-8. Summary of Tug Recommendations

Research and Applications Module (RAM)

Figure 2-9 illustrates the conclusions of this study that pertain to the RAM. It is recommended that RAM's operationally associated with the EOS include their own support provisions with the exception of the basic EOS capability that may be available during on-orbit operations. RAM's operationally associated with the MSS may depend upon support from the MSS. Free-flyer operations may be dependent upon ground control, the MSS or EOS for support. The high data transfer requirements of some RAM configurations will require Ku-band communications links. Ku-band should be included in a RAM only on an as-needed basis.

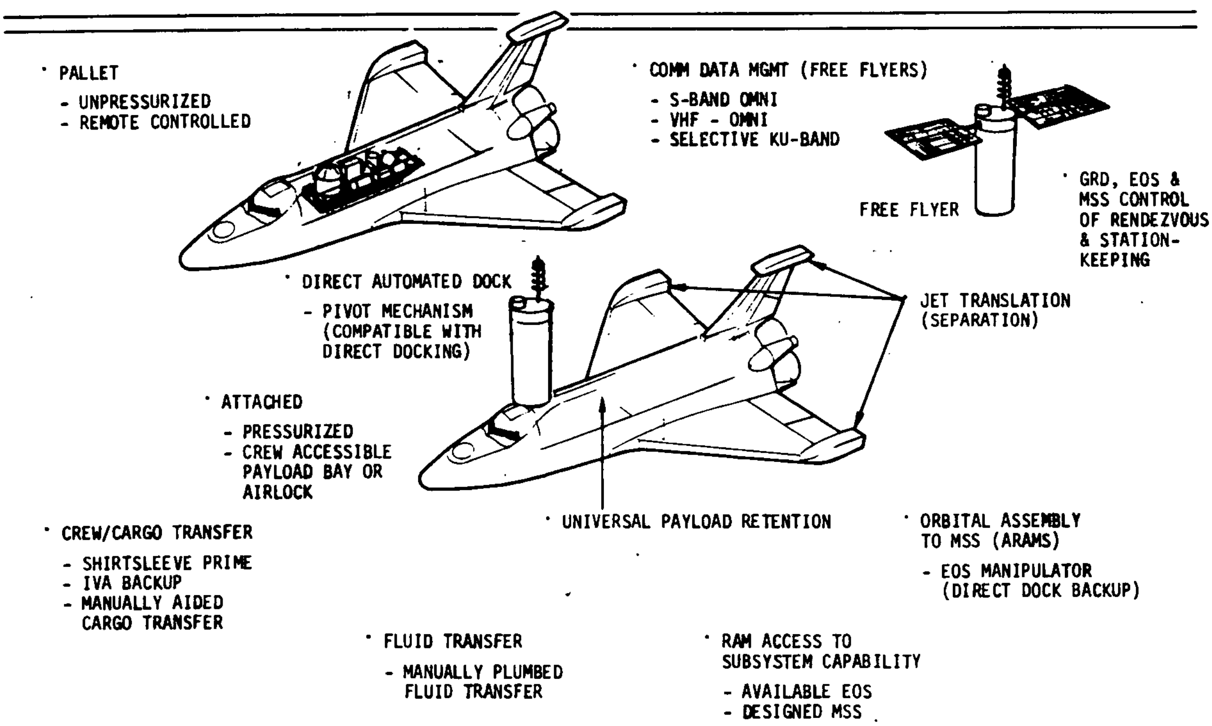


Figure 2-9. Summary of RAM Recommendations

Modular Space Station (MSS)

Figure 2-10 illustrates the conclusions of this study that pertain to the MSS. The recommendations reflect the basic concept that the MSS is an orbital support facility. Thus, VHF, S-band, and Ku-band links are recommended. Autonomous state vector update capability is required. The basic MSS should be sized to provide the necessary support to RAMs.

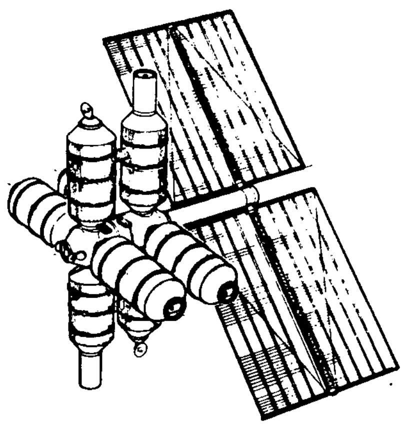


Figure 2-10. Summary of MSS Recommendations

SUGGESTED SUBSEQUENT STUDY TOPICS

Section 6.0 of this report presents a synopsis of recommended subsequent studies. It is believed that these suggested studies could enhance the results of the Orbital Operations Study by both maintaing the applicability of the data of this study and defining some of the more critical operational interfaces and design concepts to phase B or C levels. The suggested topics are as follows.

1. Orbital Operations Update. Maintenance of the data of the Orbital Operations Study to reflect updated orbital traffic models and revised element characteristics

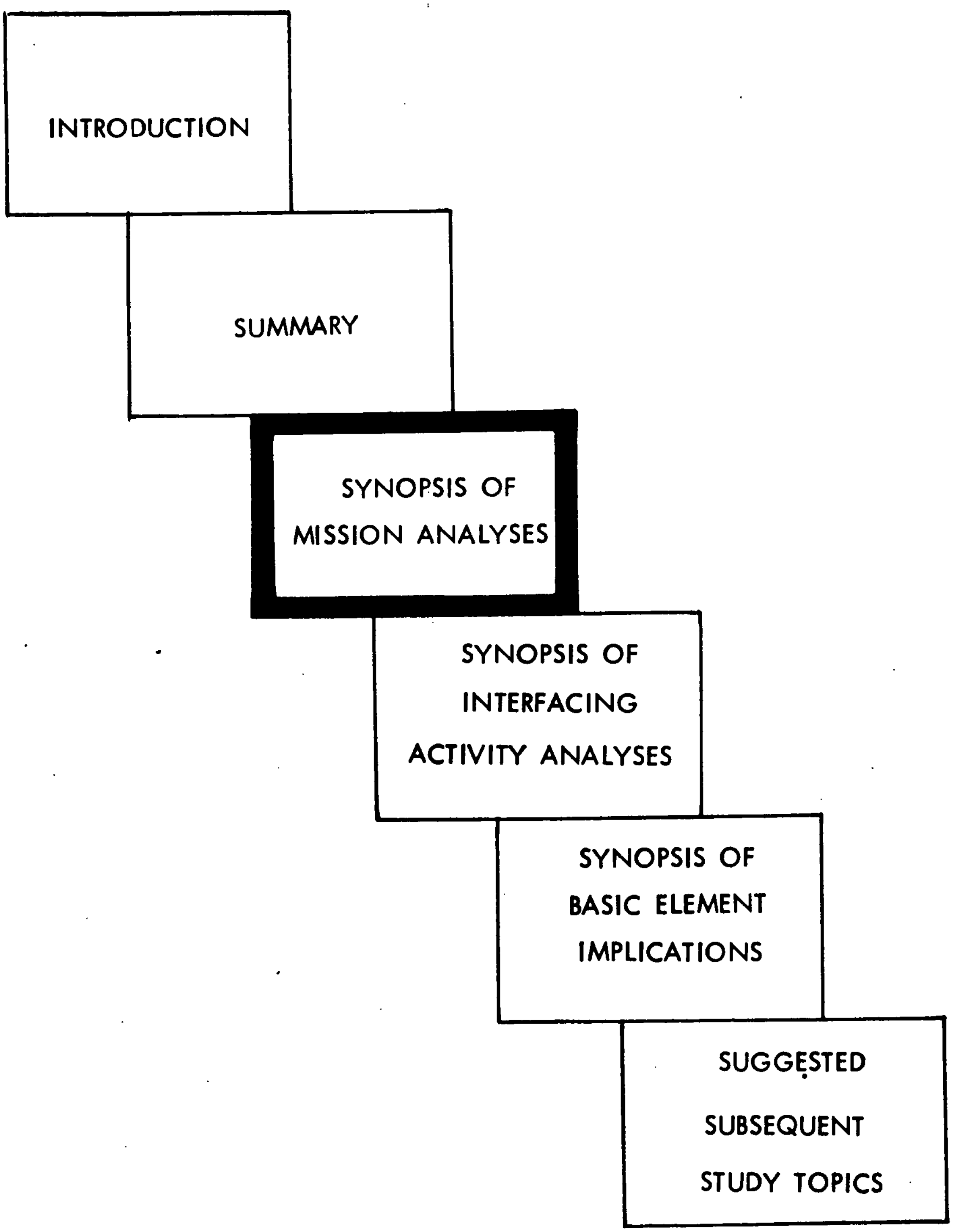
2. Integrated Data Transfer Analysis. Operations analysis of the potential interrelationships and utilization of the ground receiving stations and the numerous orbital elements proposed for the 1980's

3. Incremental Propellant Resupply of a Space Tug. Cost effectiveness of delivering incremental amounts of space tug propellant in conjunction with delivery of other payloads.

4. Docking Port Standardization. Definition of singular docking interface to be incorporated on all elements.

5. Scanning Laser Radar Development. Advanced development of space rated hardware.

6. Liquid-Vapor Interface Control. Advanced technology effort to establish practicality of capillary propellant transfer concepts.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3.0 SYNOPSIS OF MISSION ANALYSES

Mission model synthesis was conducted as the initial effort in the Orbital Operations Study. Volume I of the technical report presents the detailed results of this task. The primary purposes of this activity were: (1) to identify all reasonable element-to-element interactions that may occur during earth orbital operations, and (2) to identify interfacing activities between element pairs that could occur as a result of the interactions.

STUDY BASELINE

In order to ensure that a comprehensive list of element pair interactions was identified, an extensive literature search and review was conducted that encompassed some 200 contractor and NASA agency documents. In order to limit the scope and maximize the depth of the analyses in previous element studies ground rules had been established that limited consideration of element pair interactions to a finite number rather than all potential interactions. Forty design reference missions that were developed during individual element studies were extracted from the documentation. These missions were integrated and grouped into eleven generic mission models for purposes of this study. The generic mission models encompass not only the element pair interactions identified in the literature but also those interactions that are indicative of potential capabilities and applications of the elements. (This study was not limited to evaluation of only currently planned element-to-element interactions.)

MISSION MODELS

Table 3-1 identifies the generic mission models. It became apparent that the key to grouping was to categorize by the propulsive elements in the inventory. Almost all interactions are related to some orbital operation of a propulsive element. As the mission model titles indicate, similar mission objectives are accomplished by different mission models; only the propulsive elements are different. The term "emplacement" is used to signify the delivery of a payload to space (to become a free flyer) as opposed to the term "retrieval" which is indicative of the picking up of an on-orbit payload. "Logistics" missions are pertain to the delivery of a payload to another element, picking up a payload from an element, or a combination of both. "Sortie" missions apply to the orbital operation wherein the payload remains attached to the transport element for the duration of the mission. Staged missions refer to the operations of potential multi-staged propulsive elements such as the chemical propulsive stage cislunar shuttle. Disposal missions are characterized by the removal of expended elements from earth orbit other than by the EOS.

Figure 3-1 typifies the pictorial representation of the mission events of the models. Figure 3-2 illustrates the mission event sequence developed for each model.

Table 3-1. Generic Mission Models

VEHICLE	MISSION MODELS		INTERFACING ELEMENTS
EARTH ORBITAL SHUTTLE	MM-1	EMPLACEMENT	RAM; SATELLITE; KICKSTAGE; TUG; FIRST MOD OF MSS, OLS, OPD, CLS
	MM-2	LOGISTICS/RETRIEVAL	MSS; CLS; OLS; RAM; TUG; SATELLITE; EOS; OPD; CARGO, PROPELLANT, LSB MODS
	MM-3	SORTIE	RAM
SPACE BASED TUG	MM-4	RETRIEVAL/EMPLACEMENT	RAM; SATELLITE; CLS; TUG; OPD; EOS; MSS; OLS; OIS
	MM-5	LOGISTICS	LLT; RAM; SAT; MSS; CLS; TUG; EOS; OPD; CARGO MODS
	MM-6	DISPOSAL	CLS; OIS; OPD; MSS; OPD
GROUND BASED TUG	MM-7	EMPLACEMENT/SORTIE	TUG; SAT; RAM
	MM-8	LOGISTICS/RETRIEVAL	TUG; CLS; SAT; MSS; RAM; OPD; EOS; PROPEL, CARGO MODS
OIS	MM-9	DELIVERY	CLS; OLS; OPD; TUG
CISLUNAR SHUTTLE	MM-10	STAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS
	MM-11	NONSTAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS

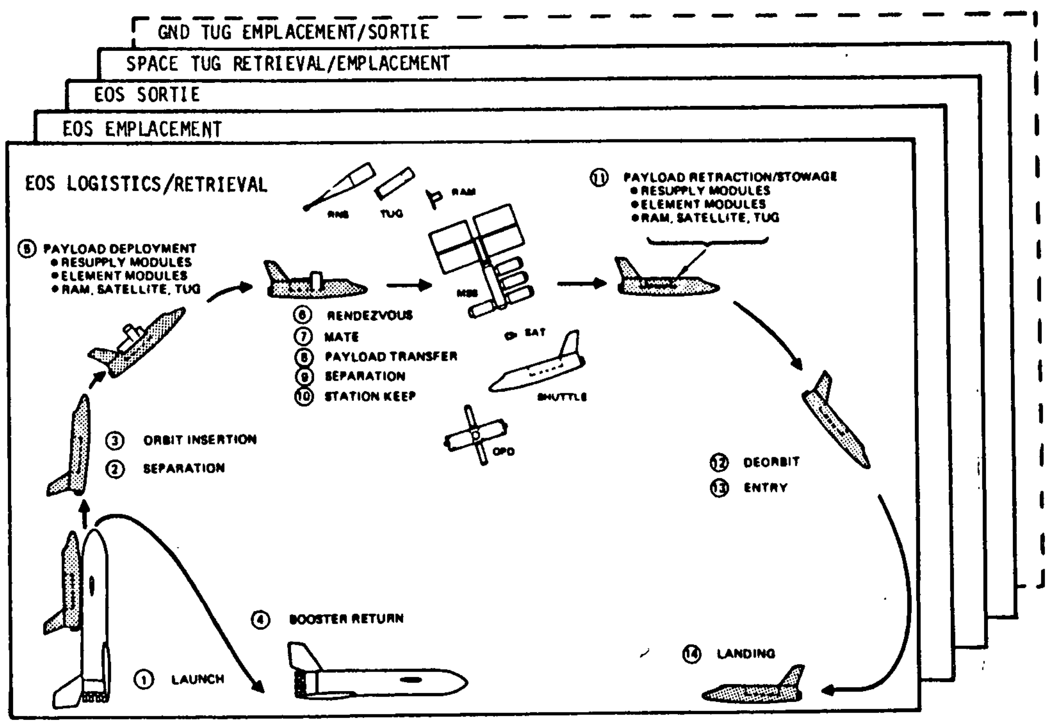


Figure 3-1. Mission Model Pictorial Representation

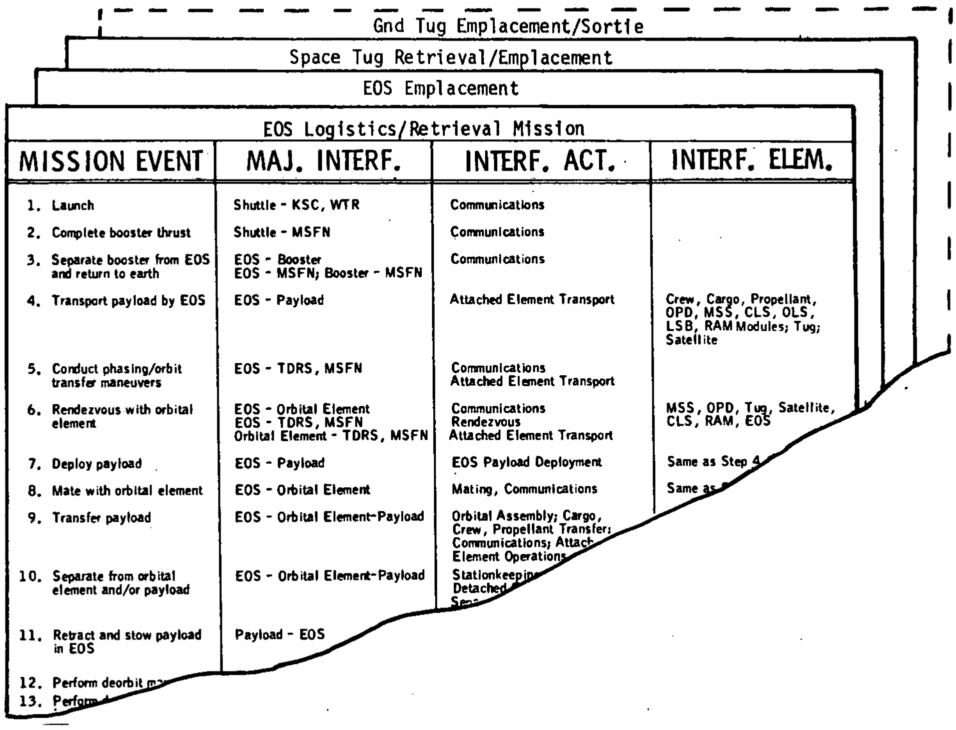


Figure 3-2. Mission Event Sequence

ELEMENT INTERACTIONS

Analysis of the models and the mission timelines provided the identification of all reasonable element pair interactions. Figure 3-3 is the element pair interaction matrix. This matrix includes all 25 study elements on both the ordinate and abscissa. There are a total of 325 matrix intersections on the chart. Of these, 117 intersections were established as potential element pair interactions and are so indicated in the non-cross hatched, numbered blocks. (The numbers are solely for reference purposes in tabulating the interfacing activities that can occur.)

The lower half of the chart would only be redundant data and is, therefore, left blank. In order to determine all element interactions for a given element, it is necessary to read down the column under the specific element to the bottom of the matrix and then across to the end of the matrix. For example, the elements that can interface with the "RAM-Detached MSS" are identified as 9 (EOS), 78 (Ground-Based Tug), 99 (Space-Based Tug), 178 (Low Earth Orbit MSS), 179 (Geosync MSS), 181 (CPS Orbital Shuttle), and 183 (Reusable Nuclear Shuttle).

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR. RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		17	18	19	20	21	22	23	24	25
TUG	NON RET											35														
	RETURNABLE											58														
	GRD BASED				73	74			77	78		80	81	82		84		86	87	88		90	91	92		94
	SPACE BASED					95			98	99		101	102	103	104	105	106	107	108	109	110	111	112	113	114	115
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														161	162		164		166						
	DET. MSS														178	179		181		183						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR. RESUP																									
	EO RESUP MODS													235	236	237		239	240	241		243	244	245		247
MSS	LOW EO														248											
	GEOSYNCH															260		262		264						
CPS	OIS																	272	273	274	275					280
	EO SHTL																	281								289
	CLS																		290		292	293	294	295	296	297
	RNS																			298	299	300	301	302	303	304
LPS	OLS																				305	306	307	308		
	TUG UNMAN																							313	314	315
	TUG MAN																							317	318	319
	RESUP MOD																							320	321	322
	LSB																								323	
	OPD																									325

LEGEND

Matrix Summation	325
Actual Interfaces	117
Interface Exists	(open box)
No Interface	(cross-hatched box)

Figure 3-3. Element Pair Interaction Matrix

As might be expected the EOS interacts with more elements (all except the Chemical Propulsion Stage) than any other element. The Space-Based Tug runs a close second. This is a reflection of the importance of these two propulsive elements as the workhorses of the earth orbital space program. In contrast, three of the elements interact with only one other element. They are the "RAM-Attached EOS", "RAM-Detached EOS", and the "EOS Delivered Satellite", each of which interacts only with the EOS (block numbers 6, 7, and 10 respectively).

Some of the interactions that are not obvious are explained below. The interactions between two EOS's (block number 1) occur only in the event of a reduce operation between two EOS's. This also is the case for the interaction between two ground-based tugs (block number 73). The RNS to RNS interaction (298) occurs because of the modular concept for the RNS, which of course, would require on-orbit assembly. Modular assembly concepts are also the reason for the interaction identification for the CPS (281 and 290), the MSS (248 and 260), the OLS (305), OPD (325), and LSB (32).

Figure 3-4 is indicative of the tabular lists developed to provide a cross reference between element interactions, interfacing activities, and mission models. With these tables it will be comparatively easy to determine if the analyses of the interactions in the Orbital Operations Study are affected as individual space element definitions, roles, and missions evolve to firm requirements.

Interface No.	Interface Pair	Interfacing Activity: Mating 1	Orbital Assy 2	Separation 3	Cargo Transfer 4	Crew Transfer 5	Propel. Transfer 6	EOS Payload Deployment 7	EOS Payload Retr. & Stowage 8	Communications 9	Rendezvous 10	Stationkeeping 11	Attached Elem. Operations 12	Detached Elem. Operations 13	Attached Elem. Transport 14	Mission Model: EOS Emplacement 1	EOS Logis/Retriev. 2	EOS Sortie 3	SB Tug Retr/Emplace. 4
1	EOS-EOS	✓		✓	✓	✓				✓	✓	✓	✓	✓			✓		
2	EOS-NON RET TUG			✓	✓	✓		✓		✓		✓	✓	✓	✓	✓			
3	EOS-RTN TUG	✓		✓				✓	✓	✓	✓	✓		✓	✓	✓	✓		
4	EOS-GB TUG	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓		
5	EOS-SB TUG	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
6	EOS-ARAM, EOS				✓	✓		✓	✓	✓									
7	EOS-DRAM, EOS	✓		✓	✓	✓		✓	✓	✓									
8	EOS-ARAM, MSS	✓	✓	✓				✓											

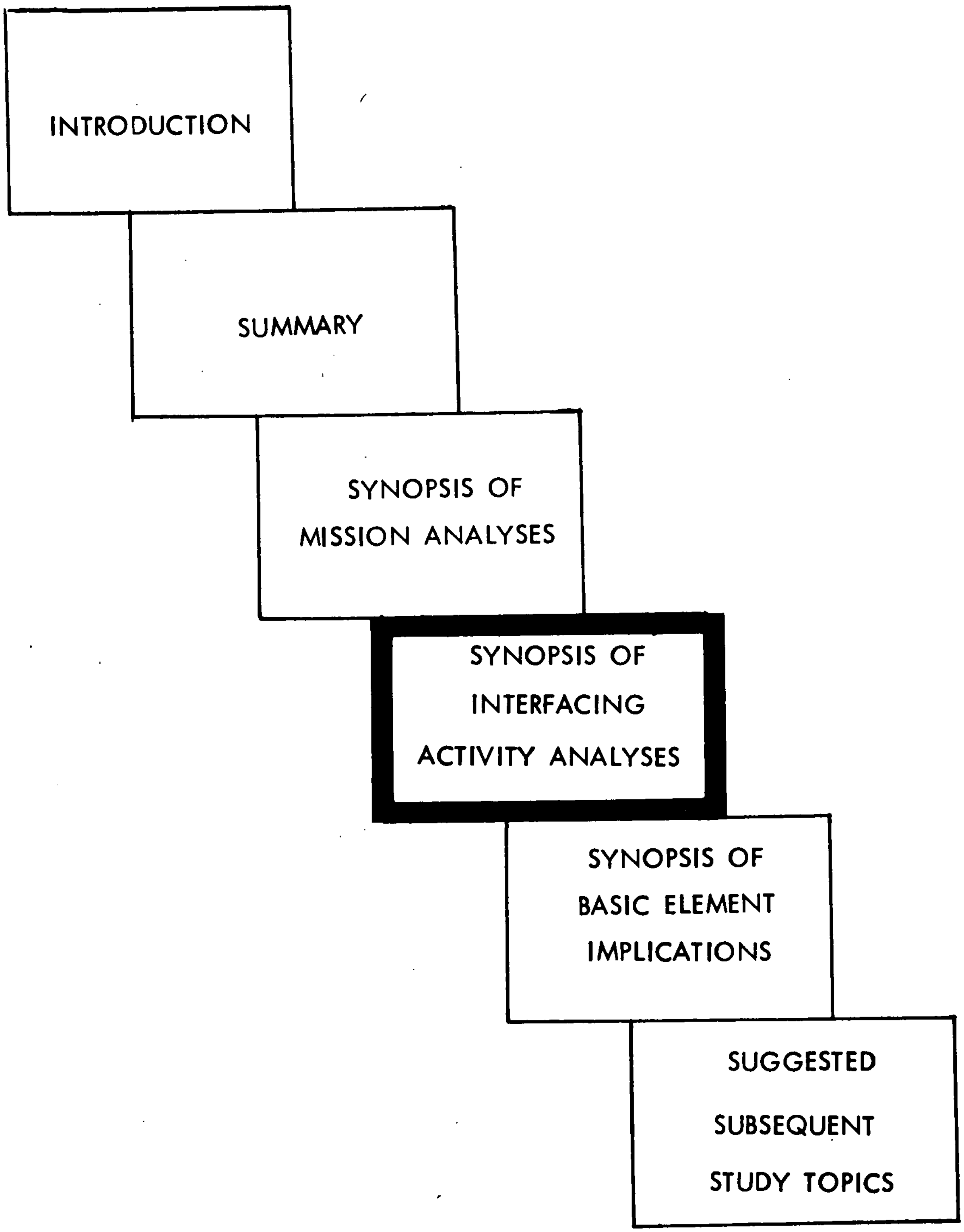
Figure 3-4. Mission Model Cross Index

INTERFACING ACTIVITIES DEFINITION

The second vital extraction from the mission models and event timelines was the interfacing activities that could occur during element interactions. Table 3-2 summarizes the 14 generic classifications of interfacing activities. The indicated grouping of activities corresponds to the presentation in the technical report. For example, the detailed analyses for the first five activities are contained in Volume II, Part 2. An attempt was made to derive a list of mutually exclusive activities; however, it was decided that some overlap was desirable and further reduction in the list would mask some key operations and functions. The summary of the analyses of each activity is presented in the next section of this report.

Table 3-2. Definition of Interfacing Activities

Volume II, Part 2	
MATING The attachment in earth orbit of any two elements (or modules), including the operations of final closure prior to contact ORBITAL ASSEMBLY The joining together of two or more major parts to form a particular configuration of a single operational element in earth orbit, or to facilitate transport to lunar orbit or high-energy earth orbit SEPARATION The physical uncoupling of two mated elements and the subsequent maneuvers required to provide adequate clearance between elements	EOS PAYLOAD DEPLOYMENT The removal of a payload from the orbiter cargo bay and readying it for operation or separation EOS PAYLOAD RETRACTION The insertion of a payload into the orbiter cargo bay subsequent to initial mating of the payload to the orbiter
Volume II, Part 3	
COMMUNICATIONS The transmission of sound, video, and digital/analog data via space links from element-to-element and from element-to-ground RENDEZVOUS The operations required to achieve close proximity of one element to another for purposes of stationkeeping and/or mating	STATIONKEEPING The maintaining of a predetermined (not necessarily fixed) relative position between two orbiting elements DETACHED ELEMENT OPERATIONS The operational support required by a free-flying element from another element and/or ground control
Volume II, Part 4	
CREW TRANSFER The transfer of personnel between two elements in orbit CARGO TRANSFER The transfer of solid and fluid cargo between two elements in orbit PROPELLANT TRANSFER The transfer of large quantities of liquid hydrogen and liquid oxygen between elements in orbit	ATTACHED ELEMENT OPERATIONS Support by one element to another attached element while the latter is operating or being serviced, checked out, or stored ATTACHED ELEMENT TRANSPORT Support by a major propulsive element to an attached payload (element or module) during transport from one orbit to another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4.0 SYNOPSIS OF INTERFACING ACTIVITY ANALYSES

This section presents a synopsis of the more significant results of the analyses conducted during the evaluation of the 14 interfacing activities. The key alternate approaches and functions, design influences, and preferred approach selections are identified for each activity.

MATING

The mating activity includes precontact, contact, and post-contact events. Precontact events include alignment of the mating vehicles and reduction of relative velocities. Contact includes capture, impact energy attenuation and relative velocity nulling. Post-contact events include transposition and berth (for the case of manipulator utilization), draw-down of the interfaces, structural alignment and rigidization, and interconnect of interfacing utilities.

Summary

Three alternate approaches were initially selected for in-depth analysis. They were direct dock, extension/retraction, and manipulator (Figure 4-1). Both manual and automatic concepts were considered in the direct dock approach. Development of the functional requirements for the approaches indicated that the extension/retraction option was not a unique approach. Within the scope of this study it was more akin to a single degree-of-freedom manipulator design concept.

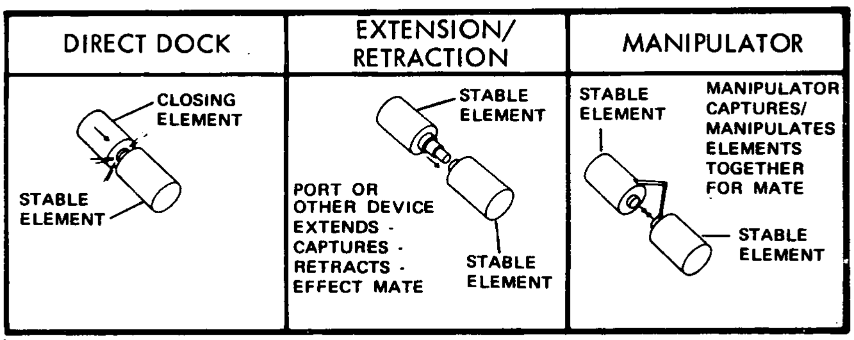


Figure 4-1. Mating Alternate Approaches

The preferred approach for mating was the direct automatic dock concept. Manual direct dock capability was also recommended as an alternate capability if a manned element were involved in the operation.

The two major design influences resulting from the approach selection were: (1) development of a standardized docking interface for all elements (except small satellites), and (2) incorporation of a scanning laser radar on all logistics elements and orbital facilities. Because of weight and size limitations on small satellites, it would be impractical to include a standardized docking port on these elements. Thus, an adapter that could provide the transition between a logistic element standardized port and a satellite attachment mechanism is also required. A manipulator could provide this function for EOS orbiter-satellite mating operations.

Discussion

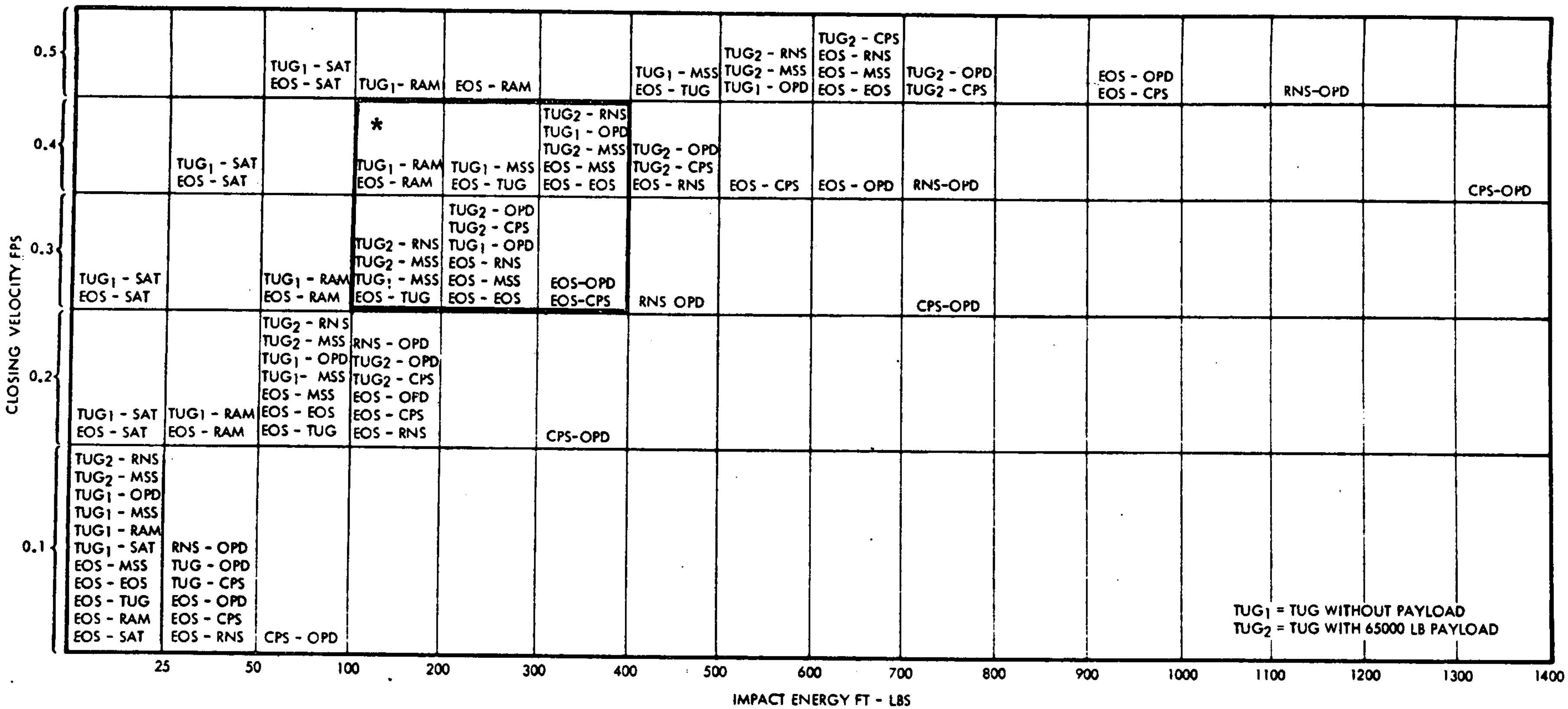
The classic example of direct manual dock is the CSM/LM docking in the Apollo program. The Russian Salyut concept is an example of the automatic/remote controlled direct dock approach regardless of the manning status of the elements involved. Although manipulators have not been used in the space environment, there has been extensive use of this approach in various hostile, earth-bound environments; e.g., under water, radiation, contaminated areas, etc.

One of the most important considerations in determining the practicability of the direct dock approach was the evaluation of impact attenuation systems. Equivalent mass characteristics of potential mating elements ranged from as low as 500 slugs (EOS-satellite) to as high as 20k slugs (CPS-OPD). The basic problem was to determine if a common docking concept could be derived that would accommodate this range of equivalent masses in the docking operation. Four docking concepts were evaluated: ring and cone, square frame, multi-probe and drogue, and the international concept. Any of the four could accommodate the mating mass spectrum (with two exceptions) with a singular attenuation design concept provided reasonable closing velocity controls were imposed. Figure 4-2 illustrates the interrelationships between element pairs, closing velocity, and kinetic energy. The emphasized area indicates the preferred design concept. Almost all element pairs can direct dock with a singular attenuation design concept of 100 to 400 ft-lb provided the closing velocity is less than 0.4 fps.

The only exceptions to the singular concept are the OPD-CPS/RNS and satellite interfaces. The first two are not considered a limitation because the results of the analyses of the propellant transfer activity indicated that an OPD was not a required nor recommended orbital element. Satellites require unique handling because of their characteristic size. It would be unrealistic to impose the incorporation of a standard docking port on a satellite that could actually be smaller and lighter than the docking mechanism.

In general, manipulators can be considered to be state of the art. However, the current status of development of manipulators for space use indicates that the following operational limitations must be assumed at this time:

1. The dynamics problem associated with mating an element attached to the extended manipulator to a close proximity stationkeeping element (the "plug in" concept) would impose unrealistic structural and control requirements on the manipulator.



*Emphasized area represents the best fit for commonality. All element pairs can direct dock with a system that attenuates 100 to 400 ft-lb impact energy if closing velocities are maintained at less than 0.4 fps.

Figure 4-2. Energy Attenuation Criteria for Direct Docking Various Element Pairs

2. Structural and dynamics problems associated with manipulators greater than 60 feet in length rapidly become prohibitive.

3. Automated manipulator operation between two unmanned elements is impractical.

4. Remote control from ground of manipulator mating is not practical as a normal operation because of the potential long duration gaps/short duration contacts of the communication links.

Table 4-1 summarizes the evaluation of the alternate approaches. Manual direct dock would be the preferred concept except that in several cases mating must be accomplished between unmanned element pairs. Thus, the preferred baseline approach for mating is direct automatic dock.

Table 4-1. Mating Concept Comparison

Concepts / Factors	Direct Dock		Manipulator Berth
	Manual	Automatic	
Technology	Preferred - state of the art	Acceptable - technology available	Least preferred - new to space
Checkout Maintenance	Preferred - least and less complex parts	Acceptable - with active elements on vehicles that can be manned or returned to ground	Least preferred - requires ground maintenance
Safety	Acceptable	Acceptable	Acceptable
Reliability	Preferred - least parts	Acceptable - with redundant sensors	Acceptable - with redundant arms
Commonality	Acceptable - still requires automatic docking	Preferred - commonality across all element pairs	Least preferred - requires direct docking and manipulator techniques
Relative Cost			
Initial	Least cost	Medium cost	Highest cost
Long term	Least cost	Medium cost	Medium cost
Operational/Design Complexity	Preferred - less operations, least complex hardware	Acceptable - least operations, complex hardware	Least preferred - most operations, complex hardware
Interfaces			
Power	Low	Medium	High
ISS	Los	High	High
ACS	None additional	Complex	Simple
Crew	Vehicle pilot	None required	Vehicle pilot and manipulator controller
Near-Term Bias	Preferred	Acceptable	Least preferred
Far-Term Bias	Preferred	Acceptable	Acceptable

The functional requirements that are applicable to the direct dock approach and reflect the capabilities of any of the four docking concepts evaluated are as follows:

Longitudinal velocity: 0.2 fps to 0.4 fps

Lateral velocity: 0.09 fps to 0.5 fps

Angular velocity: 0.06 deg/sec to 0.3 deg/sec

Lateral miss distance: plus or minus 6 inches

Misalignment (p. y. r): plus or minus 3 degrees

Vehicle attitude hold: plus or minus 0.2 deg to plus or minus 1.0 deg

As mentioned above, the exception to the direct dock approach is mating operations involving small satellites. Only the tug and the EOS mate with small satellites. In order to use the direct dock approach with these satellites, an adapter that would provide a transition between a "standardized" docking port on the tug or EOS and an attachment mechanism on the satellite is required. In the case of the EOS the adapter could be attached to a pivotal-direct dock-deployment mechanism. If the EOS is equipped with a manipulator, then obviously it would be used to effect mating between the EOS and a satellite.

The selection of a pivotal mechanism and/or a manipulator for inclusion in the EOS is dependent upon several orbital operations as well as EOS programmatics and traffic models. Based upon the traffic models used in this study, the frequency of element pair operations where a manipulator concept would be preferred did not warrant its inclusion in the basic EOS.

ORBITAL ASSEMBLY

The orbital assembly interfacing activity includes two distinct classes of operations. One is the assembly of modules of elements for orbital operations (e.g., MSS). The other is the temporary assembly of elements or modules of elements on a transport vehicle for subsequent delivery to a higher energy orbit (e.g., OLS modules on a CPS). There are always a minimum of three elements and/or modules involved when the orbital assembly occurs. Two elements being joined together is considered a mating activity. Mating and attached element transport activities are closely related to the orbital assembly activity and directly influence the orbital assembly concepts.

Summary

The two major phases of orbital assembly that were considered are (1) "Initial Mating Activities" which involve operations up to and including mate of the elements/modules to be assembled, and (2) "Post Mating Activities" which include supplemental rigidization and utility interconnect operations. The alternate approaches for the first phase are essentially the same as for mating and are illustrated in Figure 4-3. The second phase of assembly operations consists essentially of utility interconnect/rigidization operations. Figure 4-4 illustrates the alternate approaches.

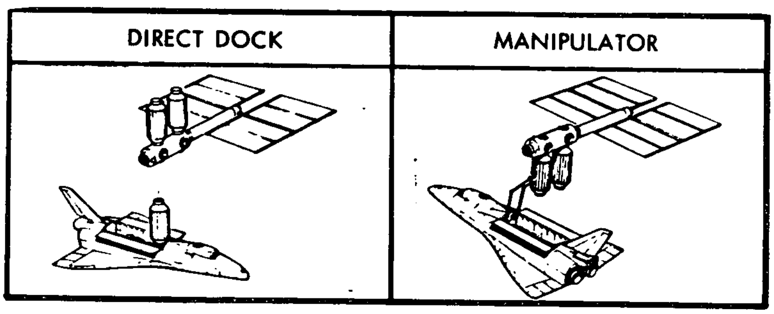


Figure 4-3. Initial Mating Options

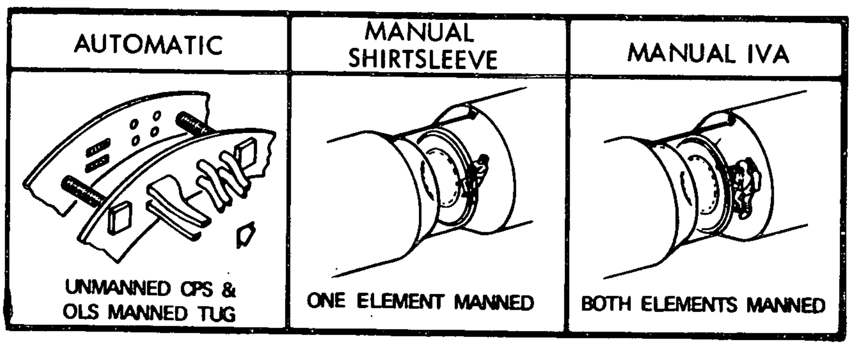


Figure 4-4. Interconnect Options

Although the manipulator was considered to be highly desirable in the assembly of the MSS, the direct dock concept was adequate and strongly preferred for the assembly of other multi-module orbital elements. Thus the singular recommendation is the direct dock approach.

The preferred approach for post-mating operations is dependent upon the manning status of the elements and the accessibility to the mating interface.

A "standardized" docking port is adequate for all assembly operations. A scanning laser radar is recommended for incorporation on the logistics vehicle to assist in the alignment and final closing maneuvers of the initial mating.

Discussion

The first phase of orbital assembly is essentially a mating operation. The approaches, design concepts, procedures and functional requirements for this phase of orbital assembly are the same as for mating. The second phase of orbital assembly is dependent upon the subsequent operations of the assemblage. If the assembly is to be an on-orbit operational element (e.g., MSS), the post-capture operations must reflect crew and cargo transfer and attached element operations. If the assemblage is to be transported by a logistics element, the primary driver of the post-capture orbital assembly phase will be the characteristics of the attached element transport operation.

Both permanent (MSS, CPS, RNS, OPD) and temporary (MSS and lunar payloads on the CPS/RNS) assemblages were examined for initial mating operations. Either the direct dock or the manipulator concept could be utilized in these assembly operations. The manipulator is considered to be highly desirable for MSS assembly primarily because of the potential margin of safety that could be achieved by the more direct control and potential automation of the placement of modules after the initial mating of the EOS and MSS. Direct dock is preferred for assembly of the CPS, RNS, and the payloads on these two transport elements primarily because the required reach of the manipulator would exceed 100 feet.

An additional consideration in the direct docking concept for assembly is the alignment problem. The length and mass of the modules involved makes it imperative that accurate alignment aids be provided. The proposed concept is to incorporate a laser on the logistics element, such as the EOS, and illuminate an extended laser reflector target complex attached to the mating interface. Figure 4-5 illustrates the concept.

Comparison of approaches for modular interchanges (MSS modules and cargo resupply modules) was inconclusive. In light of the diversification of preferred approaches depending upon the element pairs involved, it is recommended that a combined direct dock-manipulator approach be utilized for modular interchange. Integration of preferred approaches across all activities indicated that, in general, direct dock was preferred but in each activity there were certain operations that were distinctly enhanced, simplified, and less costly if a manipulator were used (e.g., multi-payload deployment/retraction). Based solely upon the anticipated frequency of these unique operations, direct dock is selected as the baseline approach. However, manipulator development and provisions for kit installation on the EOS is also recommended

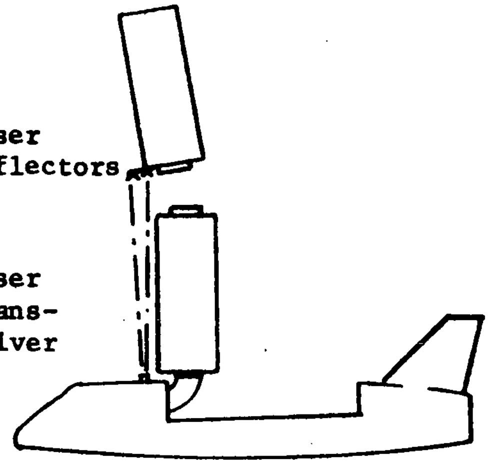


Figure 4-5. Direct Dock Assembly Alignment Concept

Rigidization of multi-module assembly on transport vehicles was evaluated in conjunction with attached element transport considerations. Many cislunar payloads (LSB, resupply modules) must be delivered in a disassembled or stacked configuration. A special multi-docking adapter is required for assembly of the lunar payloads on cislunar shuttles. The design of the adapter must be compatible with delivery to earth orbit by the EOS. This limits considerably the number of viable options for design. A design concept model (Figure 4-6) was defined in conjunction with attached element transport analyses. It consists essentially of three "beams" each with three in-line docking ports. The beams are sequentially assembled at 60 degrees angles. Note that the onboard docking ports pivot to minimize the assembly alignment problems.

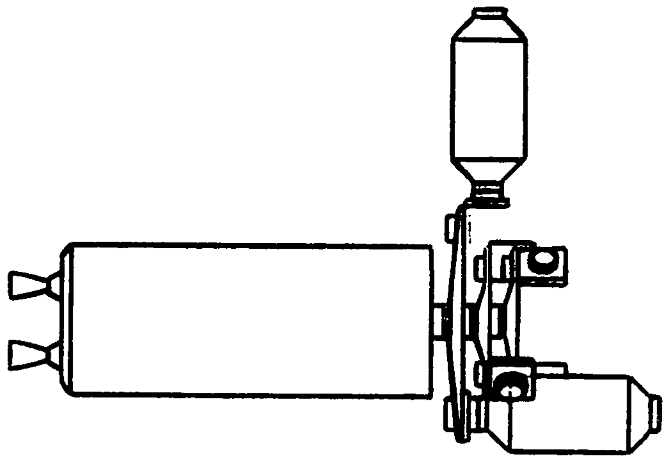


Figure 4-6. Cislunar-Shuttle Payload Adapter

The second phase of orbital assembly, post-mating operations, is closely related to crew and cargo transfer and attached element operations activities. An integrated preference is for shirtsleeve operations wherever possible. Structural rigidization via the direct docking system is adequate in all cases. Utility interconnects are required on the MSS, OPD, CPS, RNS, and some tug payloads. CPS, RNS, and tug interconnects are all recommended to be accomplished automatically. The number of interconnects between the logistics elements and payloads is quite limited in all cases because the payloads are either dormant or operating in conjunction with a separate control center. MSS and OPD (manned) interconnects can readily be accomplished in a shirtsleeve manual mode. The complexity of automated interconnects for these latter two elements is not warranted. (It was not considered a viable option--severe design impact--to provide manual access to an interface solely for interconnection of utilities.)

SEPARATION

The separation activity for this study is applicable only to elements that interface at a mating port. The activity includes pre-release events (disconnect of electrical and fluid interfaces, checkout of separation systems, hatch sealing, etc.), release (physical uncoupling of the elements from the mating port) and separation maneuvers required to provide clearance between the vehicles such that the elements can perform independent operations.

Summary

The two approaches that were evaluated for separation operations are illustrated in Figure 4-7. The preferred approach is the jet translation option. There are essentially no additional hardware requirements if jet translation is used. The primary design influence is the recognition of the potential plume impingement on the elements involved during the translation maneuver. This potential problem will be a prime driver on both the selection of the propellant and the placement of the jets.

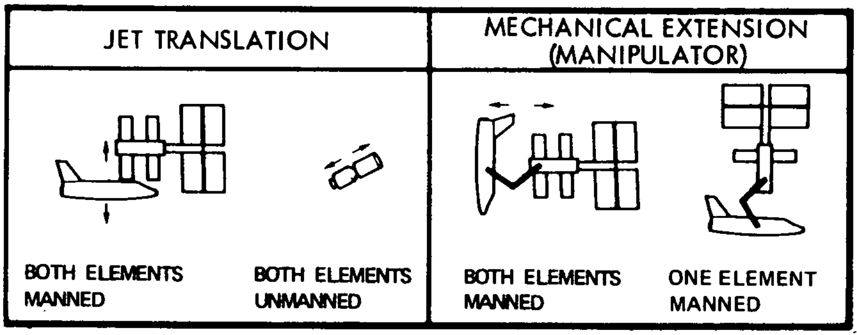


Figure 4-7. Separation Alternate Approaches

Discussion

Separation between single module elements presents no unique problems. The operations can be closely akin to the Apollo program. Separations from the EOS must account for the appendages (wings, tail) of the EOS, but all concepts currently envisioned provide adequate clearances for the separation maneuver.

Separation from the MSS is more critical. Precise alignment must be maintained because of the proximity of adjacent modules. This alignment is actually more critical for separation than for mating. The most critical time is at the minimum separation distance. At mating the alignment can reach the limit because the docking port is designed to accommodate misalignments. When separating, a corrective maneuver is required if the alignment limit is approached.

Two MSS adjacent module separation operations occur relatively frequently. They are: (1) departure of free-flying RAM's, and (2) rotation of resupply modules. The additional margin of safety that could be achieved by the more positive and direct control of a manipulator makes this approach highly desirable. However, jet translation can be made adequately safe. Inclusion of a laser scanning radar on the MSS and passive laser reflectors on the target element in a prescribed pattern can provide the necessary accuracies and control data for the operation. (The laser and reflector have been identified as required, or at least highly desired, in several other interfacing activity analyses.)

Contamination of sensors on the MSS, RAM and/or satellite is of definite concern during all thrusting maneuvers. The separation activity is a potential problem area because of the close proximity of the elements. Tugs, the MSS, and the EOS must interface with RAM's and satellites. Because the RAM and satellite transport tugs can be unmanned, the manipulator approach is not considered to be applicable. Also during the transport and stationkeeping operations, tug attitude control systems will be expelling contaminants. Therefore, both RAM's and satellites must be configured to protect contamination prone sensors either by placement or deploying shields. The potential plume impingement problem must be considered in the selection of propellants, placement of jets, and orientation of jets on all elements that either contain contamination prone sensors or interface with such elements.

Use of a manipulator to obtain a physical separation between two elements prior to jet thrusting does not, in and of itself, preclude plume impingement problems. Figure 4-8 presents one configuration of the EOS orbiter. Note that the payload is not in the jet exhaust flow until it is approximately 50 feet from the EOS. Based upon test data obtained from the exhaust of 25-pound jets (extrapolated to the 1000-pound jets proposed for the EOS), contamination of same sensors could occur at the radial distance between the payload and the jets illustrated in Figure 4-8. Again the key factor is the placement and orientation of the jets.

Figure 4-9 illustrates a different EOS orbiter jet configuration that provides an essentially contamination-free operational volume above the cargo bay. This volume is not dependent upon the use of a manipulator.

In all cases at least one of the elements involved in the separation activity has translation capability. Thus no additional hardware is required to perform the separation maneuver with jet translation. A manipulator cannot be justified for separation purposes. The preferred approach is jet translation.

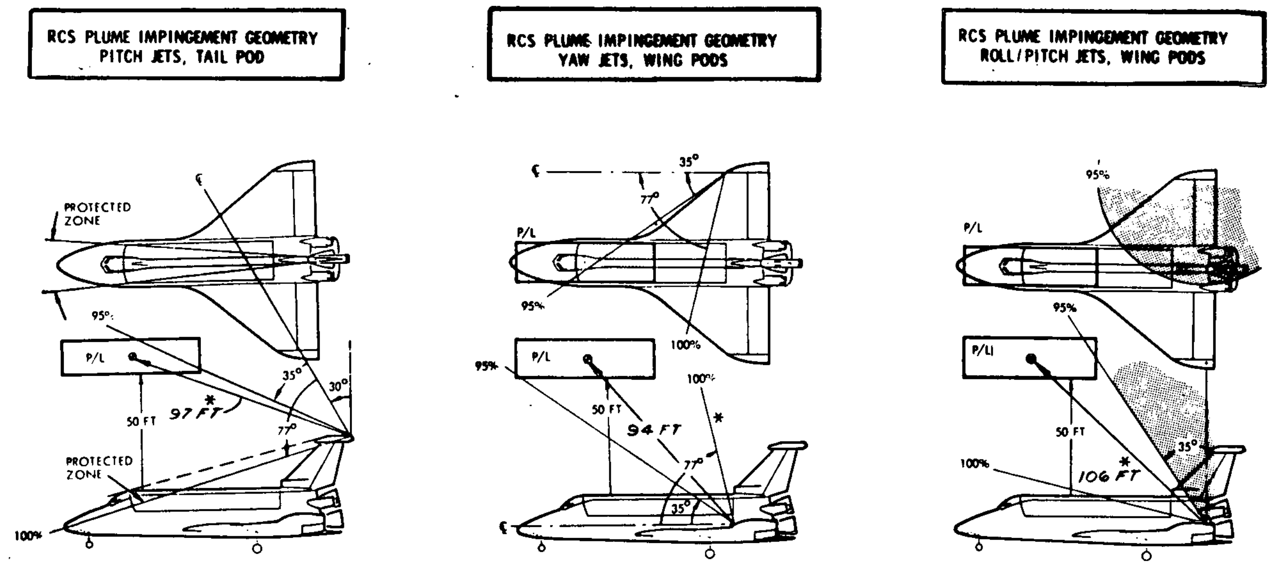


Figure 4-8. EOS Jet Configuration A

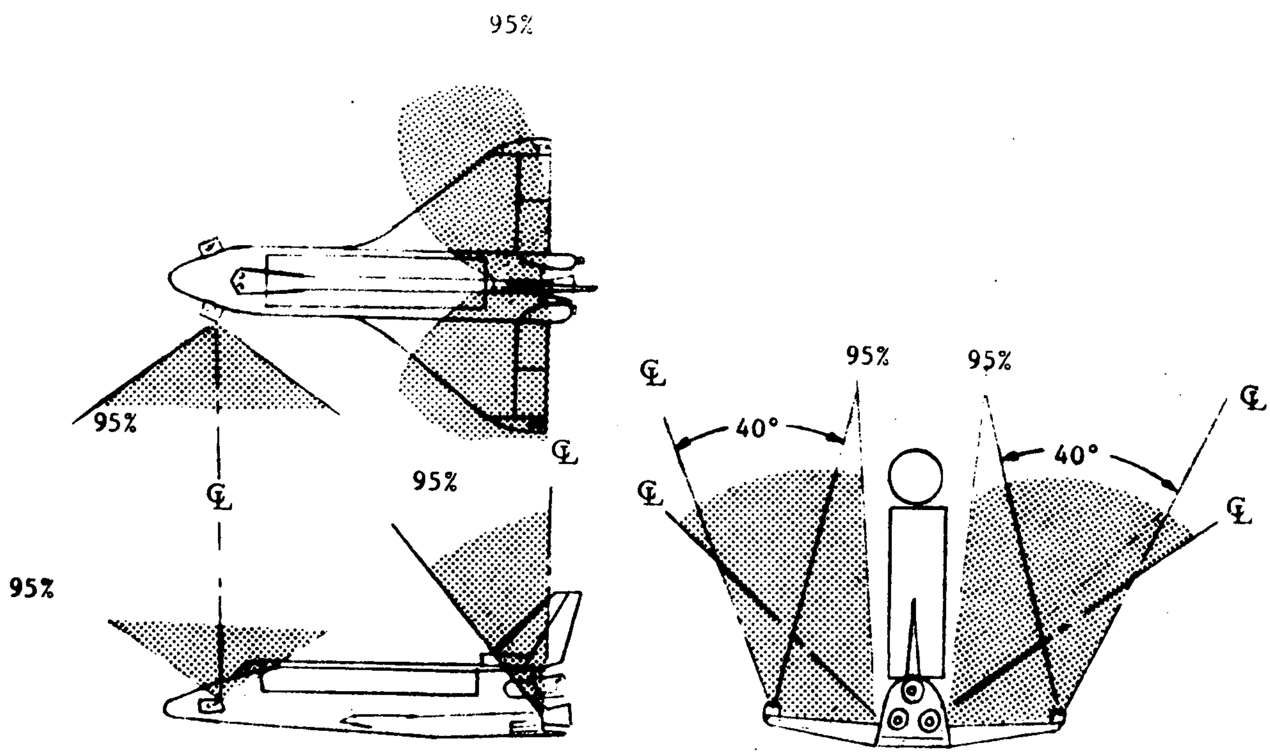


Figure 4-9. EOS Jet Configuration B

EOS PAYLOAD DEPLOYMENT AND RETRACTION/STOWAGE

These two interfacing activities are so interrelated that they can best be summarized in a combined presentation. EOS payload deployment is defined as the operations involved in releasing the payload from the retention system in the cargo bay, extending the payload beyond the EOS moldline, and if required, readying the payload for separation and/or operations. Retraction and stowage of EOS payloads is the converse or reverse set of operations.

Summary

The alternate approaches evaluated were the pivotal mechanism and the manipulator (Figure 4-10). The broad spectrum of potential payloads that the EOS must accommodate resulted in the recommendation that both approaches be developed. Based solely upon the traffic models used in this study, the pivotal mechanism approach is recommended for initial incorporation in the EOS. The manipulator approach could either be a kit installation or included in a later EOS orbiter. Detailed EOS programmatic evaluations and updated traffic models will determine the final sequence of development.

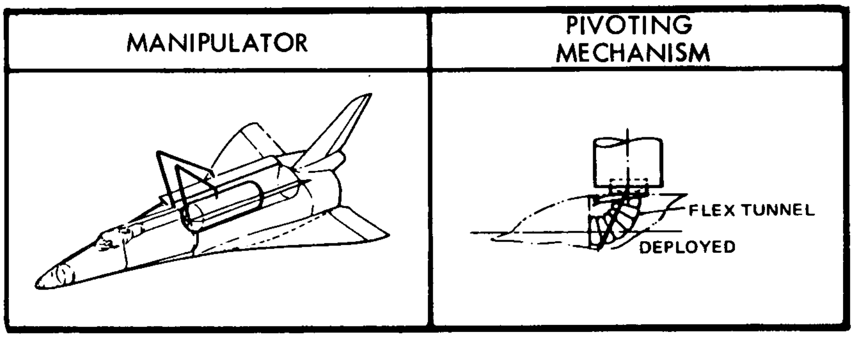


Figure 4-10. Payload Deployment/Retraction Approaches

Discussion

The pivot mechanism consists of a rotational platform that pivots about the EOS upper moldline up to 90 degrees with respect to the orbiter centerline. The pivot point can be located at either the forward or aft bulkhead of the cargo bay. If it is attached to the forward bulkhead, then the option exists for the addition of a flexible tunnel to provide shirtsleeve crew access to the payload in either the stowed or deployed positions. The manipulator concept consists of an articulated boom with multiple degrees of freedom provided by joints, elbows, and pivots. The control skill, computational requirements, and mechanization complexity increases non-linearly with the number of degrees of freedom.

The functional requirements for the two approaches are essentially the same. However, their accommodation of these requirements and the resultant design influences on the payloads and the orbiter vary significantly.

Umbilical interconnects with the payload in the cargo bay must either be automated or performed by the manipulator if it is the approach used. The additional option of manual IVA interconnect operations is available if the pivotal mechanism approach is used (assumes forward bulkhead mounting of pivot and pressurizable tunnel connecting the EOS cabin to the docking port on the pivot mechanism).

Deployment and retraction of multiple payloads is readily accommodated with the manipulator approach. Various "rack" concepts are available that could be used with the pivotal mechanism for handling multiple payloads. But the rack occupies some of the available cargo bay volume and thus, the allowable payload diameter would be smaller.

Some payloads required operation in a deployed but attached mode; others require access for deactivation, equipment safing, and appendage retraction prior to stowage. In the case of the pivotal mechanism approach, crew access can be readily accommodated through a flexible tunnel and the integral docking port on the mechanism. Also utility interconnects can be maintained from prelaunch through landing for attached element operations. The manipulator approach requires a berthing port and utility connect/disconnect operations to accomplish the same functions.

Subjective evaluations included technology status, maintenance and checkout, reliability, relative cost, and crew training. The pivotal mechanism approach was favored in all categories.

During the course of the analyses, retention concepts were also evaluated. The approaches had little impact on the retention concept. However, it was apparent that multiple attachment locations were required. Up payloads may differ from down payloads in size, weight, and/or desired orientation. In addition, a universal retention concept is highly unlikely. Some payload designs will be such that structural penetrations to react loads will either be impractical or prohibitive from a weight standpoint. These types of payloads (tugs for example) will require a clamp device or large end ring pivot or both to provide the load distribution path between the payload and the EOS attachment points.

Based upon the preceding evaluations and the traffic models used in this study the pivotal mechanism approach is preferred on the baseline or initial concept for EOS payload deployment and retraction. However, it is recommended that the development of the manipulator approach also be accomplished. Handling of multiple payloads by any means other than a manipulator will require a redefinition of payload size. In addition, the synergistic benefits that can be derived by development of the manipulator include other activities. For example, mating between the EOS and satellites can be accomplished by a manipulator without any special adapter. Also, assembly of the MSS is enhanced by the inclusion of a manipulator on the EOS.

COMMUNICATIONS

The communications interfacing activity encompasses the transfer of information between elements and to and from ground via communications links. Included in this information flow are voice, video, analog data, digital data, command/control digital signals, ranging signals, and tracking data. Each part of this information flow is an integral part of other interfacing activities and is used to accomplish a specific requirement of these other activities. Communications provide the tool to transfer the necessary information between elements.

Summary

The design implications of three potential communication links were evaluated. The three approaches are illustrated in Figure 4-11. The TDRS and updated MSFN or Ground Network models established by the NASA Space Station Working Group were used in the analysis. All three approaches are recommended to accommodate the transfer of information to and from orbital elements. The basic requirement for all free-flying elements is to include an S-band system with an omni antenna. VHF (with omni antenna) is recommended as the alternate or redundant concept to S-band equipment. TDRS links are required for data transfer rates of greater than 1 Mbps and if continuous long duration (greater than 10 minutes) contacts are required. VHF links to TDRS can be accommodated by means of an omni antenna. Ku-band links to TDRS require a steerable, 5-foot diameter antenna.

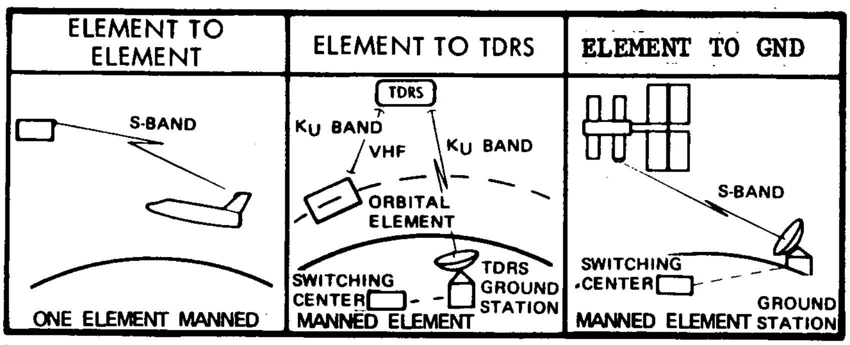


Figure 4-11. Communications Alternate Approaches

Discussion

Parametric analyses and design concept trades were conducted at VHF, S-, X-, C-, and Ku-band frequencies. There were no significant advantages to utilization of frequencies other than VHF and Ku-band (TDRS links) and S-band (ground network link). All currently defined communication requirements can be adequately accommodated at these frequencies.

A parametric study was performed to establish the hardware requirements on orbital elements operating up to altitudes of 500 nautical miles. State-of-the-art communications equipment was assumed in the calculations. The analyses indicated that only omni antennas were required on the orbital elements for VHF and S-band communication links. However, Ku-band links require a gimballed directional antenna (5-foot diameter) on the orbital elements.

Analysis of the data transfer requirements indicated that only selected RAM's, satellites, and the MSS require Ku-band communication capabilities. All other element data rates were within the 1 Mbps data rate capacity of the S-band ground network system. Low data rates (1-10 kbps) could be transfered through the TDRS VHF link. It would be highly desirable to include VHF capability in the ground network system to handle low data rate transfer requirements. S-band would still be required for data rates between 10 kbps and 1 Mbps. The preferred data links capabilities are summarized in Table 4-2

Table 4-2. Data Link Capabilities

	Forward Link (Up Link)	Return Link (Down Link)
S Band* (with ground)	1000 bps voice	51.2 kbps voice television (FM baseband 1 MHz)
Ku Band*	100-1000 bps and data up to video plus voice	Greater than 1 Mbps up to 50 Mbps and/or video plus voice
VHF (with TDRS)	100-1000 bps plus voice	100-10,000 bps plus voice

*Both S and Ku band also provide the capability for PRN ranging simultaneously with other signals.

RENDEZVOUS

The purpose of the rendezvous activity is to conduct orbital maneuvers (other than orbital maintenance) to either establish or alter a prescribed range/range rate relationship between two orbiting elements. The predominant operational mode is to conduct thrusting maneuvers on one element to position that element within close proximity of another element.

Under a broad definition of rendezvous, the injection and placement of an element at a prescribed spatial location could be defined as rendezvousing with a point in space. This operational mode involves only one orbital element and, therefore, is not considered in this study.

On-orbit rendezvous operations may either commence from a wide variation of initial orbits and terminate in a stationkeeping mode. Thus the range dispersion between elements varies from a few thousand feet to several thousand miles. The rendezvousing elements may or may not maintain line-of-sight during operation.

Summary

All three of the alternate approaches that were evaluated (Figure 4-12) are applicable depending upon the element pair involved in the rendezvous. Ground control is the predominant control approach. However, it is recommended that the EOS execute the rendezvous operations in an independent mode. Also some tug missions will require independent capability. Space control was considered applicable only in operations involving the MSS and two other elements such as a tug and free-flying RAM. Independent and space control approaches require the inclusion of autonomous state vectors and target tracking and ranging capability on the controlling element.

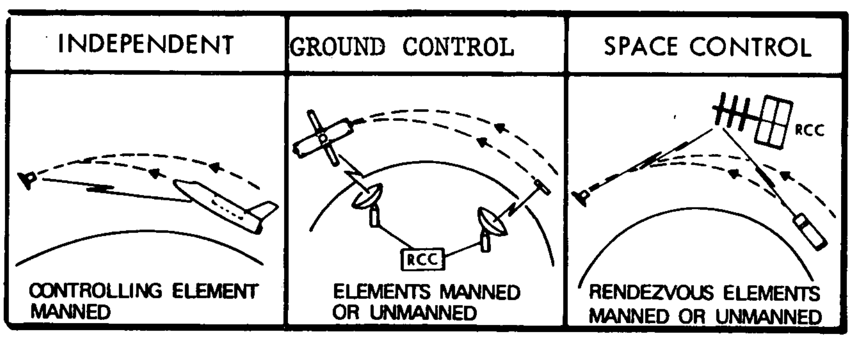


Figure 4-12. Rendezvous Alternate Approaches

Discussion

Independent operation implies that the entire activity is planned, computed, controlled, and executed by the two elements involved. Ground control and space control approaches require a control center that is independent of the two elements that are involved in the rendezvous. The key difference between the approaches is the location of the control center and the resultant equipment complement on the orbital elements.

The key functions that must be accomplished are: (1) attitude determination, (2) state vector update, (3) flight control computation, (4) relative range and velocity determination, and (5) command, control and data transfer links. The design concept model selected for the accomplishment of attitude and state vector determination by orbital elements was a star tracker/horizon scanner/inertial platform. All of these components are currently operational on space vehicles. This combination concept model can adequately achieve the performance requirements of rendezvous. Computer delta requirements for the state vector update function are estimated at 10k or 15k bits (32-bit word).

The ground network and TDRS models used in this study can provide the necessary state vector accuracies for rendezvous.

The requirements associated with flight control determination are reflected in the computer size and complexity also. A delta capacity of approximately 2k bits (32-bit) word is required for this function.

Range and velocity determination is a function of the range between the rendezvousing elements. At long range either currently operational VHF or S-band ranging with omni antennas and transponders on the orbiting elements is adequate. At close proximity ($\leq$ 5 nautical miles) a scanning laser radar (SLR) system is recommended, especially in the case of rendezvous between unmanned elements. (This SLR is also recommmended for stationkeeping, mating, and orbital operations.)

The data link requirements between elements and control center are well within the capability of the communication link requirements established by other interfacing activities or independent element operations. VHF, S-band or Ku-band can readily handle the 1 to 10 kbps command, control, and data transfer requirements for rendezvous.

The preferred approach selection was primarily influenced by the type of rendezvous missions that were applicable to the various elements.

EOS missions are relatively short duration, manned, and would be planned in detail prior to launch. In general, the preferred approach for EOS element pairs is the independent option. However, the ephemeride determination of the elements involved would be determined by ground flight control operations prior to EOS launch. Similarly, all thrust vector maneuvers would be preplanned by ground control. State vector updates during the rendezvous mission are required. Normally ground control would accomplish this function also. EOS would control only the terminal phase of the rendezvous operation in a truly independent mode.

The potential diverse short term operations/trajectories that the tug will be required to perform do not lend themselves to an independent type of approach without undue complexity and weight. A ground control approach is preferred except for terminal phase operations if the tug is manned. One class of tug missions will require the total complement of equipment except for command links to the target. This class consists of a quick-response operation in conjunction with the EOS for retrieval of a satellite. It is not recommended that all ground-based tugs incorporate the equipment complement required for independent operations.

Because of the long durations involved and the inherent independent nature of rendezvous operations involving the MSS and other orbital stationed elements, either an independent or space controlled approach is preferred. For example, MSS-RAM operations would be classified as independent. MSS-Tug-RAM operations would be classified as space controlled. However, in all operations involving the MSS ground control is still part of the overall operation. It is not proposed that the MSS maintain surveillance of all operations within its potential sphere of activity. This function is more apropos to a ground control center. Thus, before any maneuvers are commanded by the MSS, the "flight plan" must be checked and verified by a ground control center.

The CPS or RNS are limited in their rendezvous operations in earth orbit. Ground control will perform all ranging, state vector determination, and thrust vector computation functions.

In all cases detached RAM's are controlled from another element. In the case of the MSS, the RAM would conduct the maneuvers based upon commands from the MSS. RAM's required to rendezvous with the EOS would either be commanded by the EOS or be a passive-cooperative target.

Satellites and the OPD are also considered passive-cooperative targets. These elements have only the requirement to transpond ranging and tracking signals.

Based upon the preferred approach selection the resulting design influences on elements involved in rendezvous operations are summarized in Table 4-3. The EOS and the MSS require the full complement of equipment to conduct all the potential rendezvous operations that they will be involved in. The primary driver on the EOS is its requirement for quick response time and thus independent operation. The MSS, by definition, is an independent space facility and thus must accommodate all the potential operations.

Table 4-3. Rendezvous Design Influences

	EOS	Tug	CPS/ RNS	DRAM	MSS	Satellite	OPD
Star Tracker	✓	✓	✓	✓	✓		
Horizon Scanner	✓	(1)			✓		
Attitude Reference System	✓	✓	✓	✓	✓		
Scanning Laser Radar	✓	✓			✓		✓
Passive Reflector	✓	✓	✓	✓	✓	✓	✓
S-band Omni	✓	✓	✓	✓	✓	✓	✓
S-band Transponder	✓	✓	✓	✓	✓	✓	✓
S-band Ranging	✓	(1)			✓		
State Vector Computation	✓	(1)			✓		
LSR Tracking and Ranging	✓	✓			✓		
S-band Trackings and Ranging	✓	(1)			✓		
ΔV Computations	✓	(1)			✓		
ΔV Capability	✓	✓	✓	✓	✓		
Command Link	✓				✓		

NOTES: (1) It is envisioned that some ground based tug missions will require reaction times that will not permit parking orbit stay time for ground track navigation and thrust vector updates. On these selected tugs independent capability, similar to the EOS, will be required.

STATIONKEEPING

The stationkeeping interfacing activity includes those operations required to maintain a prescribed orbital relationship between two elements. This relationship can include varying range, range rate and/or attitude between the elements. The alternate approaches for stationkeeping are essentially the same as for rendezvous. The primary differences between the two activities are evidenced in the functional requirements resulting from operational differences. Stationkeeping is normally characterized by a continuous, long duration activity, close proximity operations, relative attitude constraints, and visual/video sightings (inspection/premating operations).

Summary

The three alternate approaches to stationkeeping are illustrated in Figure 4-13. As in the case of rendezvous, all three approaches are recommended. The applicability of the approach is dependent upon the element pair involved in the stationkeeping activity. The primary design influences associated with the recommended stationkeeping concepts are inclusion of scanning laser radar and video (TV) capability in all logistics elements and orbital facilities. The laser is recommended to assist in close proximity operations especially if long duration operations are desired. The video capability is to accommodate inspection operations of orbital elements.

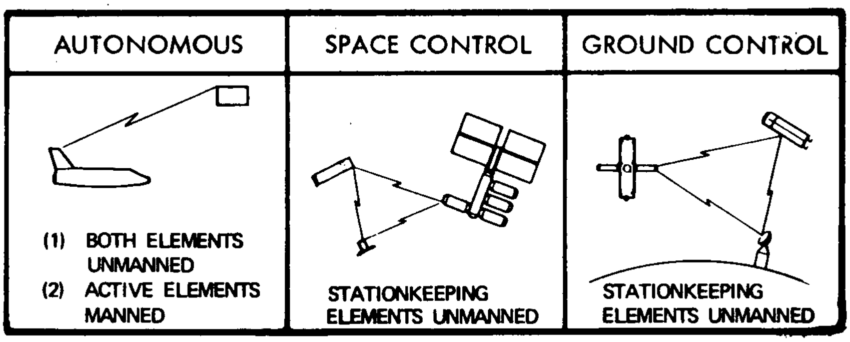


Figure 4-13. Stationkeeping Alternate Approaches

Discussion

The operating ranges between stationkeeping elements can vary from a few feet (inspection of one element by another) to thousands of miles (quiescent orbital storage of elements such as the CPS and OPD). However, the predominant modes of stationkeeping are concerned with post-rendezvous/pre-mating operations and detached element operations. A final inspection/checkout of the elements to be mated would be conducted prior to initiation of the mating maneuvers. A RAM could be deployed from either an EOS or MSS to eliminate the environmental effects of the base element but maintain a prescribed relationship with that base for control/monitor purposes of the operations of the RAM.

The functional requirements for each approach were analyzed to determine limiting factors and potential design impacts on the elements or required technology advancements. Current existing hardware concepts could adequately meet all stationkeeping performance requirements. Because of the potential duration of close proximity stationkeeping operations between manned and unmanned elements, it is recommended that range-range rate determination be automated and accuracy requirements be more stringent than currently imposed. Scanning laser radar (SLR) concepts can provide both of these functions. Accuracies of ± 4 inches and 0.1 foot/second are typical for a laser system.

An SLR is recommended for all active elements except detached RAM's. The MSS includes the laser for operation in conjunction with detached RAM's. Thus all elements that stationkeep with the RAM have a laser.

Video (TV) was identified as a requirement for stationkeeping solely for inspection purposes. It could be made a kit but basic provisions should be incorporated because of the high frequency of "inspection" operations prior to mating.

Both command and data transfer requirements can be accommodated by S-band omni equipment on the elements. All elements involved in stationkeeping include this type of equipment. In addition all elements that are either controlled or are the target require S-band transponders. It is recommended that all elements be equipped with passive laser reflectors.

Examination of the element pairs and the potential stationkeeping operations that may occur between elements indicated that the predominant mode was either inspection or premating (close proximity). For all element pairs involving manned elements operating in close proximity, the autonomous mode was selected. If only unmanned elements are involved, the autonomous mode is also preferred; however, the data from the SLR should be transmitted to a remote control center for potential command updates. Video data transfer will also be required if the stationkeeping operation is for inspection purposes.

Space control of tug/RAM or tug/satellite long-range stationkeeping operations by the EOS was considered. However, the potential communication gaps, due to the difference in orbits (e.g., EOS at 100 nautical miles; tug/RAM at 500 nautical mile altitude), and the ranges involved indicated that the approach was impractical. Ground control is considered the most efficient and least complex approach for this class of operations.

One unique long range stationkeeping operation was identified. Detached RAM's associated with the MSS could operate at considerable range from the MSS. Normally the approach would be for ground control to direct the operation. However, the mission concept is based upon the MSS directing the activities of the RAM. (Otherwise, the RAM should be considered as an EOS delivered/serviced/retrieved element controlled by ground.) Therefore, the autonomous approach was selected for this element pair also. This imposes the requirement on the MSS to range, track, and determine the state vector of the RAM. In all other autonomous stationkeeping operations only the relative position of the elements involved were required to be determined.

The primary factors that influenced the preferred approach selection were the manning status of the elements involved and the range between elements. In general, if long ranges were involved the ground control approach was preferred. If a manned element was involved in the operation the capability for autonomous stationkeeping was also recommended. The autonomous approach is preferred for all close proximity stationkeeping operations regardless of the manning status of the elements involved. However, it is recommended that, if feasible, close proximity stationkeeping operation between unmanned elements be scheduled and conducted during available ground control contact periods.

Table 4-4 summarizes the design influences and preferred approach selections for all the elements for the stationkeeping interfacing activity.

Table 4-4. Stationkeeping Design Influences and Preferred Approach Selections

Primary Element	Preferred Approach/Design Influence
EOS	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
Tug (Manned)	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
Tug (Unmanned)	Ground Control Stationkeeping Operations (Autonomous at close ranges) Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
MSS	Autonomous Stationkeeping Operations Independent state vector determination Target vehicle state vector determination capability Laser scanning radar Video (TV) capability, S-Band omni data links Detached element control capability Passive laser reflectors
CPS/RNS	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
All Other Elements (including RAM)	Autonomous and Ground Control Stationkeeping <u>Target</u> Operations Passive laser reflector, S-Band omni data links

DETACHED ELEMENT OPERATIONS

Detached element operations encompass all element-to-element interfacing support necessary to operate a spatial element that is separated from its control center. Either an orbital element or a ground station can be employed as the operational control center.

There is a significant interrelationship between this activity and communications, rendezvous, and stationkeeping. Communications treats the link geometry and hardware concepts for transferring of data. Rendezvous and stationkeeping are concerned with the generation and use of specific types of data. Detached element operations are concerned with the required data transfer rates for space experiment/application operations as well as rendezvous and stationkeeping operations. Communication link constraints are superimposed upon the potential data transfer options.

Summary

Two general approaches were evaluated: (1) ground operations and control, and (2) space operations and control. The ground control approach was further subdivided into three options: (1) direct from element to ground, (2) via another orbiting element to ground, and (3) via TDRS to ground. The approaches are illustrated in Figure 4-14. The quantity and type of data to be transferred are prime considerations in the preferred approach selection. The preferred approaches for low data rates associated with rendezvous and stationkeeping operations were discussed previously. High data rates that are characteristic of space exploration/exploitation require a different assessment of the approaches. Data transfer rates up to 1 Mbps can be accommodated by the S-band direct to ground link. Higher data rates require a TDRS link to ground. Only the MSS is recommended as a controlling/data processing orbital facility. The primary design influences that result from the application of the preferred approaches are the requirements for data comparison/screening and the sharing of the links by numerous elements.

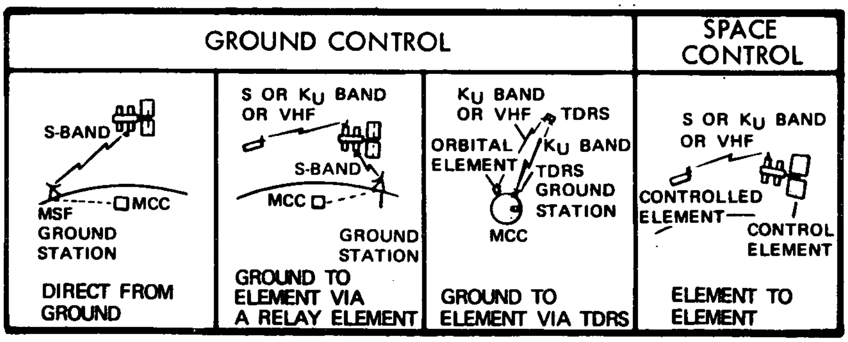


Figure 4-14. Detached Element Operations Alternate Approaches

Discussion

Detached element operations are the prime drivers on the establishment of communication link design concepts for all elements. In order to comply with the ground network and TDRS models used in this study, only VHF, S-band, and Ku-band transmission frequencies are applicable.

Low data rates (10 kbps) associated with rendezvous and stationkeeping operations can be adequately accommodated by the direct-to-ground approach for EOS, tug, CPS, and RNS operations when long ranges between elements are involved. At short ranges, space control or element-to-element links are preferred. S-band is the preferred link for these operations. However, VHF is recommended as the alternate or redundant design concept.

High data rates were identified for satellite and RAM operations. In the case of the EOS-RAM interface, only the capability of the EOS link to ground (S-band - 1 Mbps), which was established for other activities, is proposed for RAM data transfer purposes. Any additional requirements should be met either integrally in the RAM or in kit form on the EOS and considered to be part of the RAM. Imposing the requirement for a Ku-band (with directional antenna) or complex and bulky data storage equipment in the baseline EOS for a comparatively rare interface operation is not warranted.

Accommodation of high data transfer rates between the MSS and RAM is warranted. The MSS is considered an orbital facility and at least initial processing and data evaluation should be accomplished on the MSS. The high data rate capability (Ku-band) on the MSS is also required because of attached RAM and integral experiment operations that will generate composite data exceeding S-band capabilities.

Only transponding rendezvous and stationkeeping functions are recommended between satellites and other elements. All data should be transferred to ground either via S-band to the ground network or through TDRS if the data rates exceed 1 Mbps.

S-band omni communication links are recommended for all elements. Up to 1 Mbps data rates can be accommodated on this link. Selected RAM's and satellites as well as the MSS should incorporate TDRS links. VHF is required to request the use (order wire) of the Ku or high data rate TDRS channel, and also is recommended on the secondary data link.

Continuous data communication was impractical in almost all cases. Data storage concepts were evaluated to establish the feasibility of delayed data dumps. Current magnetic tape concepts are adequate. Laser systems that are currently being developed will provide margin and growth potential. However, the problem of data transfer is not resolved simply by storage and playback concepts. Table 4-5 indicates the potential contact and data processing constraints associated with the ground terminals. In addition, all potential users of either the ground network or the TDRS must realize and recognize that the data handling capabilities of these concepts will not be dedicated to support of the operations of their individual element. As many as 100 orbiting elements will be operating simultaneously by 1990; this would impose a significant scheduling constraint upon TDRS users.

Table 4-5. TDRS/Ground Network Coverage Comparison

Parameter	Ground Network (1)		TDRS Network (2)
	Orbits		Orbits
	90^{o}/100 n mi	55^{o}/240 n mi	90^{o}/100 n mi or 55^{o}/240 n mi
Percent of orbit coverage	3.2 percent	10.3 percent	> 90 percent
Maximum gap between contacts	6 hr, 30 min.	7 hr, 15 min.	
Average contact	3.2 min.	6.0 min.	
Data sink capacity/orbit	5.0×10^{8} bits	1.7×10^{9} bits	$\simeq 2.5 \times 10^{11}$ bits
Line capacity to switching center			
Real time	1.3×10^{7} bits/day	4.2×10^{7} bits/day	4.0×10^{12}
Post pass (3)	1.5×10^{9}	1.6×10^{9}	Not applicable

(1) Goldstone, Madrid, Honeysuckle Creek, Rosman and Fairbanks ground stations per NASA model

(2) Two TDRS satellites, equatorial orbit at 15^{o} and 145^{o}W. Ground station located next to switching center

(3) Assumes recording and dump at ground stations

The paramount conclusion from the analysis of detached element operations is the very strong requirement for data compression. The proliferation of unrelated orbital elements and operations within the next 15 to 20 years will saturate any reasonable ground network. Limitations on measurements and sample rates must become more stringent. Incorporation of techniques that will limit data transfer to only significant deltas from previous readings are highly recommended. Also, integration of the individual element missions will be required. Selection of orbits, relative placement in an orbit, real time data transfer scheduling, and playback or data dump scheduling are all factors to be considered in subsequent mission integration analyses.

CREW TRANSFER

The crew transfer activity involves the transferring of personnel from one element into another attached element. This study concentrates specifically on personnel transfer between elements and the interfaces associated with this transfer, but does not pertain to personnel transfer within a multi-module element.

Summary

Crew transfer may occur between manned elements, from a manned to an unmanned element, and in pressurized or unpressurized conditions. Normally, unpressurized crew transfer will occur between a manned element and a non-mannable element. Figure 4-15 illustrates the basic approaches for normal crew transfer operations.

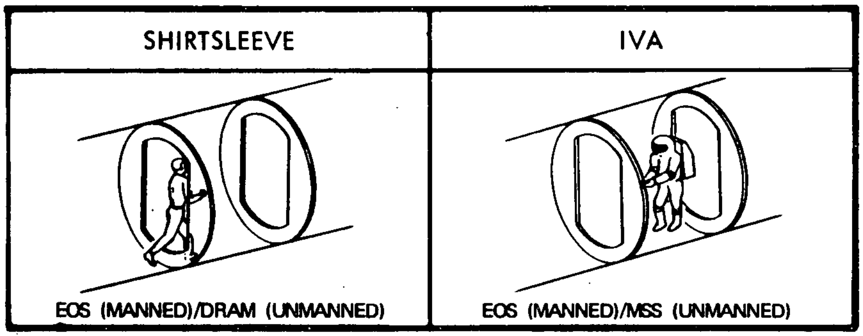


Figure 4-15. Crew Transfer Alternate Approaches

The preferred approach will vary depending upon the elements involved and the purpose of the transfer. Shirtsleeve transfer is preferred for all normal crew rotation and cargo transfer functions (e.g., MSS, CPS, RNS, and space tug). Infrequent operations such as resupply or on-orbit maintenance of unmanned elements would not warrant inclusion of provision for shirtsleeve crew transfer. Thus, EVA would be preferred in these cases. Based upon the traffic model used in this study, EOS crew transfer operations with unmanned elements seldom occur. An integral airlock in the EOS is not warranted for this interfacing activity.

Discussion

The predominant criteria used in identifying the preferred approach are: (1) the capability of the elements to sustain life support functions (mannable versus non-mannable), (2) frequency of trips, (3) anticipated cargo traffic and characteristics, and (4) frequency and type of operation to be accomplished upon completion of transfer. Normal crew rotation and cargo resupply, frequent trips, high cargo traffic, and regularly scheduled operations all favor shirtsleeve operations. The inclusion of provisions for shirtsleeve transfer for infrequent maintenance or unique operations in non-mannable elements is unwarranted.

All EOS and tug crew rotation interfaces are identified as being shirt-sleeve. All MSS and CPS/RNS (manned) interfaces are also shirtsleeve either because crew rotation occurs, trips are frequent, or the cargo traffic is high.

The approach for crew transfer to a RAM is dependent upon the particular configuration. Normally, all RAM's attached to the MSS will require frequent ingress/egress operations and should be conducted in a shirtsleeve mode. RAM's attached to the EOS vary considerably. Ingress/egress provisions to the EOS cabin should be provided, but the life support provisions and, if necessary, an airlock should be provided as part of the RAM hardware complement.

It is assumed that manned access to free-flying RAM's will be relatively infrequent. Including manning provisions in this class of RAM's would not be warranted. The MSS should include provisions to pressurize the RAM or provide an airlock for IVA entry. EOS servicing of free-flying RAM's is a small percentage of the total traffic model. Kit provisions are preferred for providing manned access to RAM's associated with the EOS. The same rationale applies to other non-mannable elements that the EOS will be required to service. An airlock kit is the recommended design concept.

A crew transfer interface between a manned tug and a non-mannable element would be related to maintenance/resupply operations. This particular type of an operation is considered to be quite remote and would not warrant either an integral airlock on the tug or the development of an airlock kit for the tug. If this operation is required, it is recommended that the basic safety guideline requiring an airlock for IVA be waived and the tug crew compartment be utilized as the airlock. The concept is comparable to the current EVA operations of the Apollo program.

Table 4-6 summarizes the more significant design influences resulting from the preferred approach selections. Note that monitors, sensors, and view ports are required for verification of the habitability of an element prior to crew entry. The hatch size was based upon the minimum clearance for passage of a crewman in currently defined pressure suits. Potential cargo sizes result in an integrated hatch size requirement of 41 inches minimum.

Table 4-6. Crew Transfer Design Influence Summary

Hardware	Element Applicability
Airlock	EOS only (kit installation)
Habitable environment monitor	EOS, MSS, Tug, CPS, RNS, OLS
Environment sensors	MSS, RAM, Tug, CPS, RNS, Resupply Modules, OLS
Docking port view window	EOS, Tug, RAM, MSS, CPS, RNS, Ressuply Modules, OLS
Minimum 30-inch hatch (1)	All elements

(1) Cargo transfer requires 41-inch hatch

CARGO TRANSFER

The cargo transfer interfacing activity encompasses the operations associated with the transfer of packaged cargo and fluids between elements. Transfer of large quantities of propellants to storage depots or propulsive elements is defined as the propellant transfer activity and is not included under cargo transfer.

Summary

The alternate approaches for package cargo transfer are illustrated in Figure 4-16. Manual unaided is the preferred approach for all element pairs except those involving resupply modules.

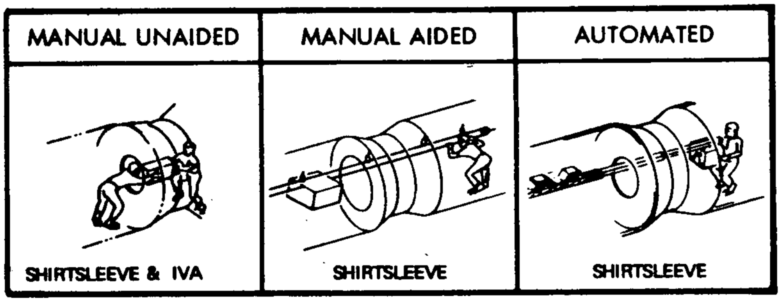


Figure 4-16. Packaged Cargo Transfer Alternate Approaches

Fluid transfer alternate approaches are illustrated in Figure 4-17. If the interface is accessible, the manual plumbed approach is preferred. A design concept is proposed that meets safety requirements and provides flexibility in individual element configurations. The automatic approach is preferred only in those cases where unmanned or non-mannable element pairs are involved.

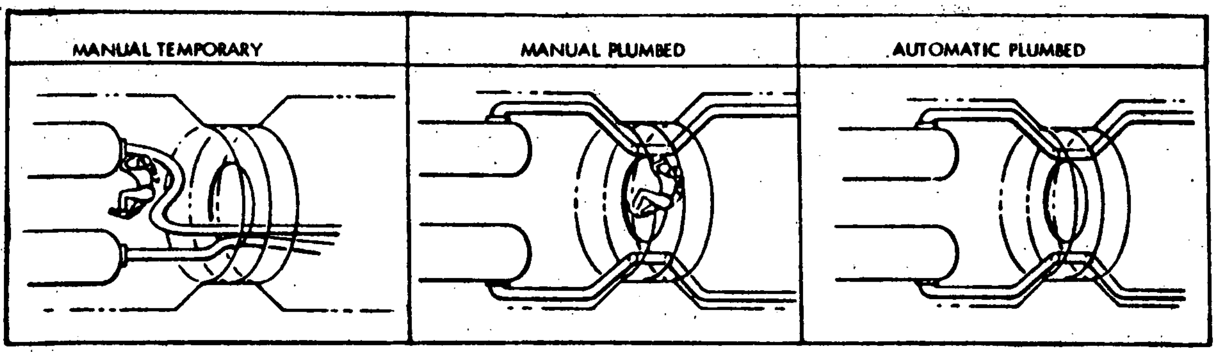


Figure 4-17. Fluid Cargo Transfer Alternate Approaches

The predominant factors governing the preferred approach selection for packaged cargo transfer are cargo size, quantity to be transferred, travel distance, and the available crew mode. The analyses indicated that an automated system is unwarranted except in the case of satellites. The potential resupply items varied from small hand held items to a Control Moment Gyro (CMG). The CMG replacement for the MSS requires a clearance of 38 inches. An additional 3-inch clearance was arbitrarily added to arrive at the maximum hatch opening requirement of 41 inches in diameter. (Crew transfer minimum was 30 inches.) All four docking concepts can accommodate a hatch opening of this size.

The inclusion of resupply modules in the space program directly affects the selections. It is assumed that this element will be used to resupply orbital elements such as the MSS, OPD, CPS, RNS, and OLS. Thus, the cargo transfer interface between these facilities and the logistics vehicles is simplified. (Tug-resupply module cargo transfer interfaces are reduced to replenishment of the tug's own consumables.) The anticipated cargo transfer from the resupply module to user elements (except the tug) will be of significant size and quantity that a manually aided system is recommended for resupply element pairs.

If the element pair interface is accessible either in a shirtsleeve or an IVA mode, the manual plumbed concept is preferred. In all other cases (e.g., unmanned element pairs) the automatic concept is required. The temporary manual plumbed concept for fluid transfer is undesirable. In this approach fluid transfer lines occupy crew transfer space, the lines are susceptible to collisions with either cargo or crew, emergency separation is not feasible, and procedures are complex.

Figure 4-18 illustrates a concept for manual plumbed interconnect. Adequate space between the pressure bulkheads of mated vehicles (assuming one of the four docking concepts evaluated in this study is used) is available for installation of this concept. The rigid lines on both elements are outside the pressure shell of both elements. These lines are terminated in valves and connectors between the end hatch of a module and the docking port mating interface. A coupling is manually installed between the two stubbed lines for fluid transfer. A temporary miniature airlock cover is installed over the interconnection.

The one cargo interface that requires unique handling is the satellite with its logistics vehicles. The EOS-to-satellite interface requires some type of capture device to initially "mate" with the satellite. Either a second device could be used to interchange modules automatically or the first device could position it at a pressure hatch and the interchange be accomplished manually in an IVA/EVA mode. The same options apply in the case of a manned tug servicing a satellite. However, unmanned tug servicing of a satellite will require remote controlled manipulator operations. From a commonality standpoint an automatic resupply concept would appear to be favored for satellites. However, satellites are usually unique, dedicated configurations for specific reasons. Therefore, each satellite must be individually evaluated and design trades as well as operational trades must be conducted to define a preferred approach.

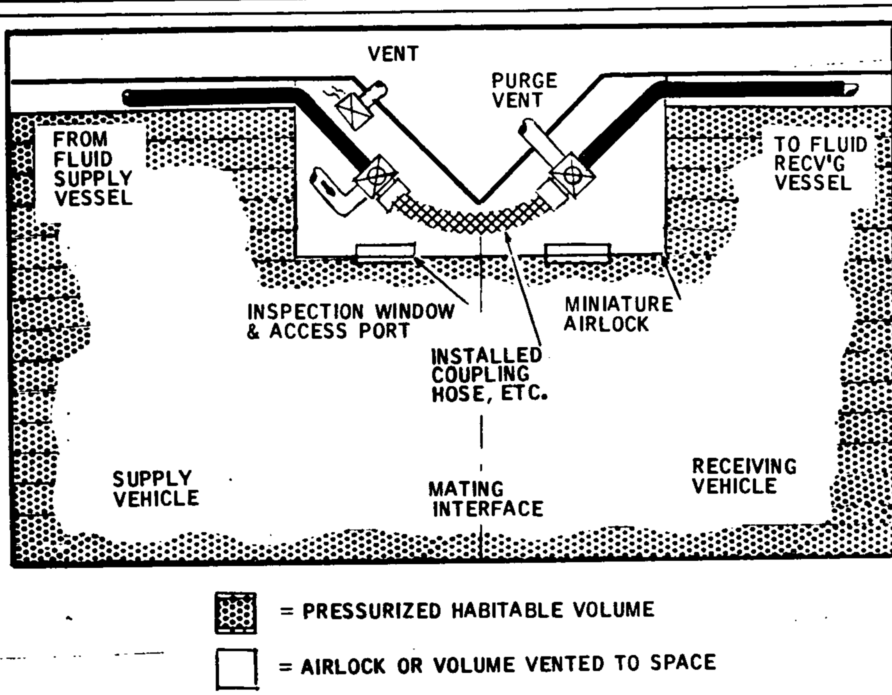


Figure 4-18. Manual Plumbed Fluid Connection

Except for satellite and unmanned-to-unmanned element interfaces the impact on the various elements to accommodate bulk cargo transfer is minimal. A single manual-aided concept should be included in the elements that interface with resupply modules.

Automated interchanges between unmanned elements and with some satellites will be required. However, these operations will be very infrequent and the device(s) should be a kit installation on the logistics vehicle. Fluid transfer to satellites and between unmanned elements are also very infrequenct operations. Automatic provisions for this function should also be a kit installation on the logistics vehicles.

The manual-plumbed concept is a significant design influence on all elements and their docking concept. In the section on mating it was pointed out that a common docking system was feasible. Similarly, the generic fluid interconnect concept discussed above illustrates that commonality across elements is feasible. Future studies on docking system optimization/standardization should incorporate a common fluid interconnect concept with at least the operational characteristics of the one developed in this study.

Tables 4-7 and 4-8 summarize the preferred concepts for packaged and fluid transfer.

Table 4-7. Packaged Cargo Transfer Summary

Approach	Applicable Element Interfaces
Manual Unaided	All EOS interfaces except some satellites* All tug interfaces except some satellites*
Manual Aided	MSS Internal MSS - RAM's MSS - Resupply Modules OLS - Resupply Modules OLS Internal Some satellite interfaces*
Automated	Some satellite interfaces*
*Preferred approach is dependent upon satellite configuration.	

Table 4-8. Fluid Transfer Summary

Approach	Applicable Element Interfaces
Manual Temporary	None
Manual Plumbed	All EOS interfaces except some satellites* All MSS interfaces All manned tug interfaces except some satellites* All resupply modules** All OLS interfaces Some satellite interfaces*
Automated	Some EOS-satellite interfaces* All unmanned tug to unmanned element interfaces Some tug to satellite interfaces* Some satellite interfaces*
*Satellite interface preferred approach is dependent upon the satellite configuration and the bulk cargo transfer concept. **Does not include propellant resupply modules	

PROPELLANT TRANSFER

The propellant transfer interfacing activity pertains to the transfer of large quantities of liquid oxygen and liquid hydrogen propellants in orbit for use by vehicle main propulsion engines. The transfer of relatively small quantities of propellants for attitude control systems, and the transfer of other liquids and gases is included in the cargo transfer interfacing activity.

Summary

The transfer of propellants from an element to the user vehicle in earth orbit can be accomplished in either of two basic ways; i.e., by fluid transfer or by modular transfer. Figure 4-19 shows these two approaches pictorially and illustrates one possible logistics option for one element pair. The modular transfer illustration shows a tug being refueled by an exchange of propellant tanks; i.e., an empty tank being exchanged for a full tank. This is sometimes referred to as the tank-set concept. The fluid transfer illustration shows a tug (which incorporates integral tanks) being refueled from a propellant logistics tank.

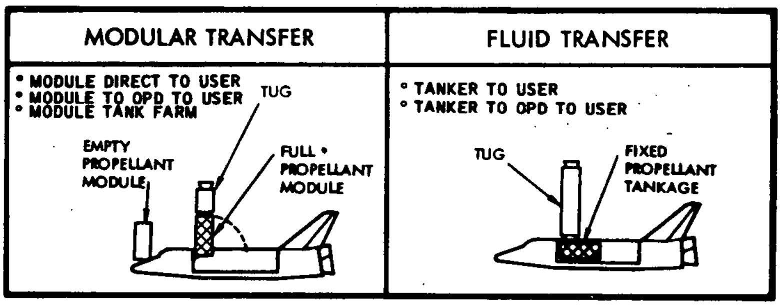


Figure 4-19. Propellant Transfer Alternate Approaches

The preferred approach for propellant transfer is fluid transfer from a propellant logistics tank delivered directly to the user vehicle via the EOS. The transfer operation should be performed with the logistics tank/user vehicle separated from the EOS. Linear acceleration, provided by jets on the logistics tank module, is preferred for liquid/vapor interface control.

Discussion

The alternate approaches depicted in Figure 4-19 are applicable to refueling of the CPS and RNS as well as the tug. Several logistics options are also indicated. Figure 4-20 presents the complete matrix of options evaluated. The primary comparison is between the modular (or tank set concept) and fluid transfer of propellants.

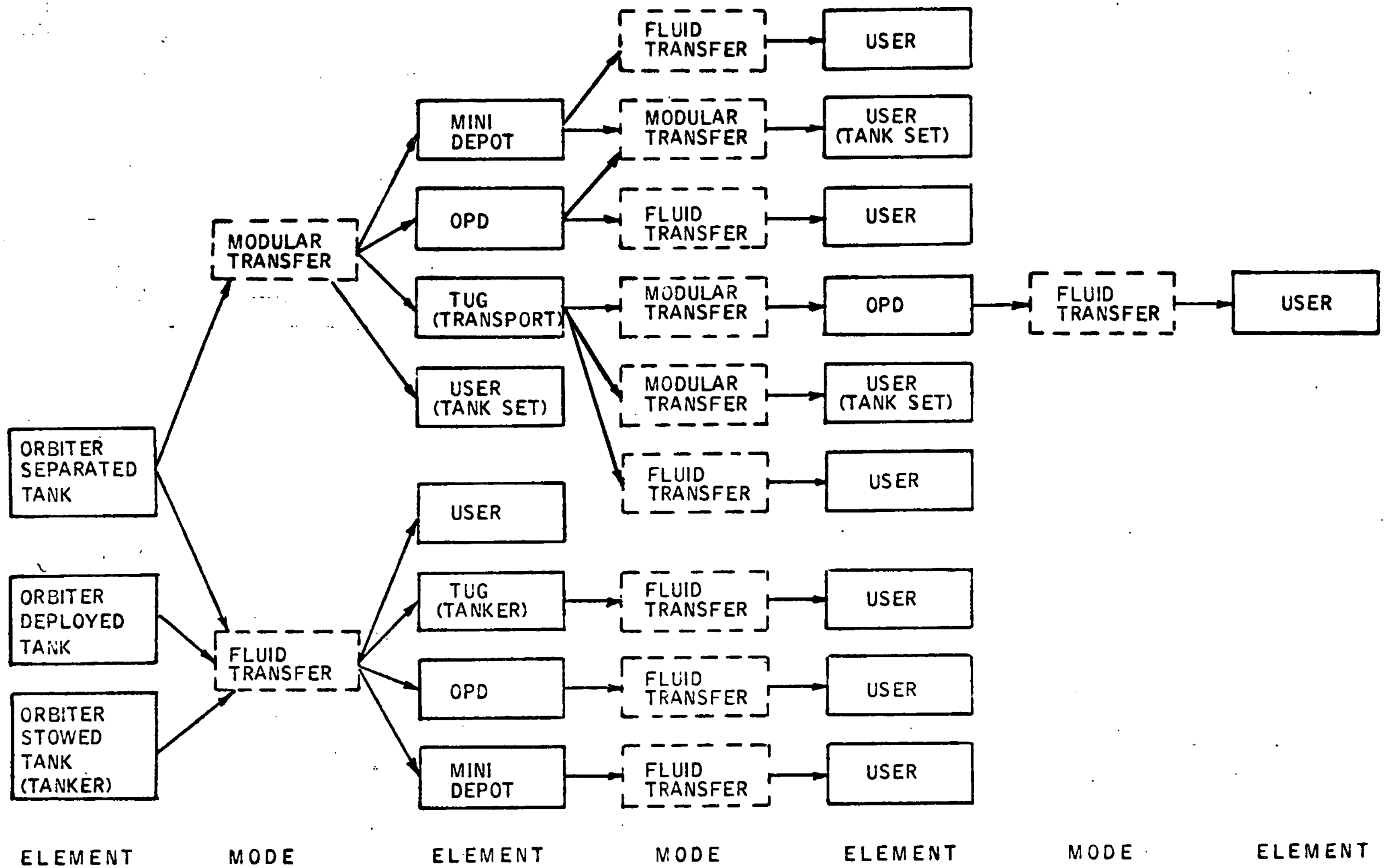


Figure 4-20. Propellant Transfer Logisitics Options

An evaluation was made of the relative weight penalties on the user vehicle imposed by the modular (tank set) and fluid transfer concepts. The criticality of weight penalties on the user vehicle is illustrated by the fact that a typical space tug requires approximately eight pounds of propellant to transport each additional pound of tug weight to geosynchronous orbit. The evaluation indicated the tank-set concept would result in additional weight to the user because of such requirements as ground insulation, provisions for handling full tanks both on the ground and in space, and additional capacity for in-transit boiloff. Also, the size of individual tanks would be smaller with the tank-set concept than with permanent tanks on the user vehicle. A dual propellant cryogenic resupply module that weighs 65,000 pounds (the payload limit of the EOS) is approximately 40 feet long. Concepts incorporating permanent tanks on the user vehicle could be delivered to orbit empty, thus permitting a tank length of 60 feet (maximum allowable length of EOS payloads).

The use of the space-based tug as an intermediate transport vehicle between the EOS and the CPS or RNS was also evaluated. Analysis of the EOS payload delivery capability indicated that the EOS can deliver a 65,000-pound payload directly to the operational parking orbit of the CPS or RNS (180 nautical miles at 31.5 degrees inclination) by consuming the EOS OMS abort propellant. Thus, the tank interchange between the tug and EOS is not required nor cost effective.

The development of an orbital storage facility for CPS and RNS logistics resupply was not warranted. Both elements will be required to provide long-term storage of their propellants during normal operations, and approximately 10 and 20 EOS flights are required to replenish the RNS and CPS, respectively.

A depot for tug propellant storage was also considered not to be cost effective. However, subsequent integrated mission analysis studies may indicate more efficient EOS payload utilization can be achieved by delivering incremental propellant loads to a mini depot and thus offset the costs associated with the depot's development.

The preferred approach for propellant transfer is as follows:

1. Delivery of a propellant logisitics module by the EOS directly to the user operational orbit.

2. Direct fluid transfer from the logistics module to the user

3. Conduction of the transfer operation between the logistics module and the user independent of (free-flying) the EOS.

4. Control of the liquid/vapor interface by logistics module thrusting (1×10^{-4} g); attitude control provided by user.

ATTACHED ELEMENT OPERATIONS

Attached element operations designate that interfacing activity in which one element provides operations support to another attached element while the latter element is being stored, operated, or serviced/checked out. The support could be monitoring the attached element while it is in quiescent storage, removing exposed film and supplying expendables during periodic servicing, or providing operational services such as orientation or pointing of the attached element. Other examples of operational support considered under attached element operations are pressurization of an attached element to permit crew visitation, data transfer and analysis, supply of electric power, and thermal control.

Summary

There are three alternate approaches defined for attached element operations; independent, dependent, and modular dependent (Figure 4-21).

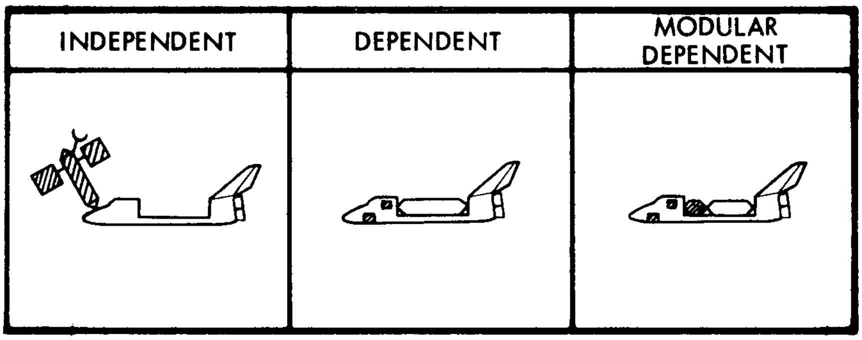


Figure 4-21. Attached Element Operations Approaches

The dependent approach was preferred if the support element was classified as an orbital facility (e.g., MSS). The modular dependent approach was preferred if the frequency of attached element operations involving the support element was a low percentage of the total operations of that element (e.g., EOS). If the attached element required unique operational support, such as arc-second stability, the independent approach (capability contained in the attached element) was preferred. Other then modular add-ons, it is recommended that EOS support to on-orbit attached element operations be limited to access to the available basic capabilities of the EOS.

Discussion

The three alternate approaches were evaluated for three potential operational modes: (1) servicing and checkout, (2) quiescent storage, and (3) on-orbit operations.

Service and checkout operations involve an interface between two elements wherein the supporting element provides such functions as replenishment of consumables, system stimuli, and response monitoring. A typical service and checkout mission would involve a free-flying RAM returning to the MSS or EOS. As the MSS is classified as an orbital facility, all functions except perhaps thermal control should be provided by the MSS. EOS servicing of a free flyer is a relatively infrequent operation and inclusion of provisions for service and checkout of the free flyer in the basic EOS would not be warranted. A modular approach is preferred. It could be in the form of modular or packaged additions to the EOS or an entire module carried in the cargo bay.

Only orbital facilities such as the MSS or OPD are applicable support elements for quiescent storage of another element in an attached configuration. The orbital facility should be initially defined to include the capability for support of quiescently stored elements. RAMs, tugs, and resupply modules may be stored at the MSS. A resupply module and a CPS/RNS may be stored at an OPD.

The only two applicable element pairs for the operations mode are the MSS-RAM and EOS-RAM. However, the approach evaluation is significantly more complex than the other two modes and, therefore, was conducted at the functional level. The primary functional requirements evaluated were communications, data management, environmental control, thermal control, attitude control, and electrical power.

The basic definition of the MSS implies that it is an orbital facility primarily dedicated to conducting space experimentation and application operations. Although separately identified in the inventory, MSS associated RAM's should be considered as a basic part of the MSS. Therefore, RAM support requirements should normally be supplied by the MSS. There are, of course, a few exceptions. As the MSS concept is modular and the RAM's will be unmanned, the RAM's should provide their own emergency oxygen hardware. Similarly, atmospheric temperature control and waste management (peculiar to the particular RAM equipment) should be provided by the RAM's. Basic attitude control of the MSS is of the order of ± 0.25 degree pointing and ± 0.05 degree per second rate stability. More stringent requirements should be provided within the RAM's (either independent or modular dependent).

The basic criteria in assessing the desirability of the EOS incorporating capabilities to accommodate attached RAM operations were: (1) the relative frequency of the requirement and (2) the impact upon the EOS. Although the near-term bias favors EOS acccommodation, the traffic models used in this study indicated that attached RAM operations through 1990 are less than 5 percent of the total EOS flights. Thus, the general conclusion is that the EOS should not be customized for attached RAM operations. However, equally important is the conclusion that basic EOS capabilities that would be available during earth orbital operations should be made available to all payloads. A summary by major function is presented in Table 4-9.

Table 4-9. EOS-RAM Support Interface

Function	Approach			Rationale
	Dependent	Independent	Modular	
Communications				
Tracking	✓			EOS Basic
Voice	✓			EOS Basic
Data				
< 1 Mbps	✓			EOS Basic
1 to 10 Mbps			✓	Mod to EOS TV Link
10 to 50 Mbps		✓		Requires Ku Link or Tape Storage
Data Management		✓[1]	✓[2]	1. Applies to Mannable RAM's 2. Utilizes Space in EOS for Unmanned RAM's
Environmental Control		✓		Limited Usage, EOS Impact
Thermal Control		✓		Limited Usage, EOS Impact
Attitude Control				
> 0.5°; 0.05°/Sec	✓			EOS Basic
< 0.5°; 0.05°/Sec		✓	✓	Experiment Unique
Electrical Power				
< 500 W Avg - 20 KWH	✓			EOS Basic
> 500 W Avg - 20 KWH			✓	Limited Usage, EOS Impact

ATTACHED ELEMENT TRANSPORT

The attached element transport interfacing activity includes the physical/structural and operational support provided by a logistics element to an attached payload during orbital transfer operations. The structural support is primarily related to the accommodation of thrust loads and load distribution concepts. Support functions are similar to those of rendezvous and attached element operations.

Summary

The alternate approaches to attached element transport (Figure 4-22) depict the two logistics vehicle options. Internal attachment is, of course, applicable only to the EOS. The external attachment option is applicable to tugs, CPS, and RNS logistics vehicles. On-orbit thrust loads of the EOS are significantly less than launch and reentry loads. All payload retention requirements are based upon launch/reentry loads. No orbital operations were identified that would require EOS orbital transfer with a payload deployed from the cargo bay. All of the four basic docking ports evaluated could accommodate the axial thrust loads operated by the tug, CPS or RNS. However, delivery of multiple payloads/elements/modules by the CPS or RNS requires a special adapter to limit bending moments to a tolerable level. No operational support requirements that were either unique or in addition to those identified in rendezvous and attached element operations were defined.

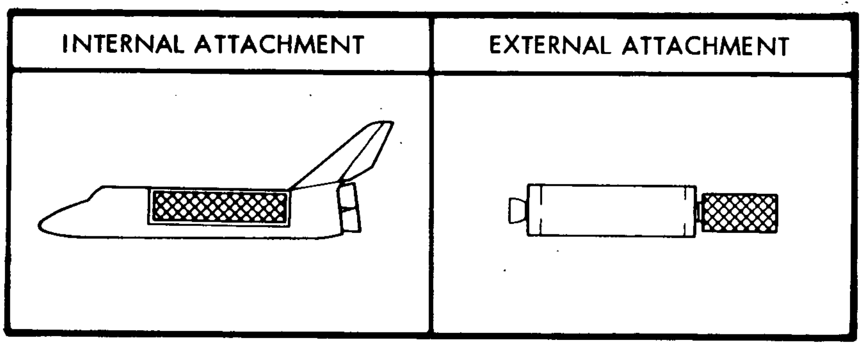


Figure 4-22. Attached Element Transport Alternate Approaches

Discussion

The obvious major functional requirement is an adequate structural interface to withstand the loads during thrusting maneuvers. The anticipated EOS maximum dynamic loads during launch and landing are: $N_x = \pm 3.0$ g; $N_y = \pm 0.5$ g; and $N_z = \pm 2.5$ g. On-orbit maneuver loads are considerably less (<0.2 g). Numerous concepts have been proposed for payload retention in the cargo bay. Analyses conducted in conjunction with the payload deployment and retraction interfacing activities indicated that multiple retention concepts--support rings, clamps, and point interconnects--are required. Also multiple retention or attachment mechanisms are required on single EOS flights because of the potential difference in up and down payloads.

All These concepts can be designed to accommodate the loads of EOS on-orbit maneuvers. The governing criteria are the launch and landing loads. No requirement was identified for EOS maneuvers with a payload deployed or berthed external to the cargo bay.

Thrust loads experienced during transport of payloads by logistics elements other than the EOS (external transport) can be grouped into two categories:

1. Loads within the capability of a standard docking concept
2. Loads requiring special adaptations

All transport element pairs utilizing any of the four docking concepts evaluated (ring cone, square frame, multi probe and drogue, and international) can accommodate axial thrust loads generated by the tug, CPS or RNS. Table 4-10 summarizes the axial loads that payload/logistic element interfaces may experience. It is assumed that a loads distribution transition cone from the docking mechanism to the CPS, RNS, and tug structure is a basic design of these elements.

Table 4-10. Interface Loads

Configuration	Thrust (Lbs. x 10^{-3})	Axial Load at Interface (Lbs x 10^{-3})
Tug/Tug	70.2	35.1
Tug/RNS		55.9
Tug/MSS		11.8
Tug/RAM		11.8
CPS/OLS (Fully Fueled)	960.0	133.6
CPS/OLS (Nearly Empty)		590.0
RNS/OLS (Fully Fueled)	75.0	22.6
RNS/OLS (Nearly Empty		47.2

The transport of the geosynchronous MSS or OLS presents a unique situation. Both the geosynchronous station and the OLS may be assembled and checked out in low earth orbit prior to transfer to their higher energy orbits. The LSB is not configured for orbital assembly and checkout. Two obvious approaches for transport of the station are either in the assembled mode or disassembled/stacked module mode. Analyses conducted in the OLS study indicated that delivery was feasible in the assembled mode by a 75,000-lb thrust RNS. However, bending moments at the junction of the appendages and the core modules can approach two million inch-pounds. Analysis of one contractor mating port concept indicated that an additional 250 pounds of structure would be required at each port on the core modules. Delivery by a non-throttleable CPS (960,000-lb thrust) in an assembled state was impractical. Bending loads at the junction of the core module and its radially mounted modules would approach 12 million inch pounds. The modules must be transported in a stacked/clustered configuration.

Several concepts were considered that would facilitate assembly and be structurally adequate. The major problem was to derive a concept that could be carried to orbit in a 15-foot diameter EOS cargo bay. Various "petal" arrangements were examined but none could be contained within a 15-foot diameter. A concept that will fit in the cargo bay, provide adequate structure, and facilitate the assembly process consists of three individual docking adapter "beams" with three docking mechanisms in line on each side of the beam. The outboard docking mechanisms on one side of the beam are hinged to facilitate attachment of modules. Upon completion of assembly in orbit the beams are aligned in 60-degree increments. It is imperative that the modules be stacked as close together as possible for the thrusting maneuver. In-line attachment with the desired spacing between modules is not considered feasible even with a manipulator assisting; use of a direct docking approach is even more unlikely.

A prime alternate concept to the "beam" approach is similar to the technique for assembly of the modular RNS or CPS. A central core module, approximately 12 feet in diameter, is used as the main interconnect between modules. Multiple pivotal docking ports are mounted on this core module. As each module is mated to the core, it is pivoted in line (major geometric axes) with the core and "latched" to the core. Figure 4-23 illustrates this concept.

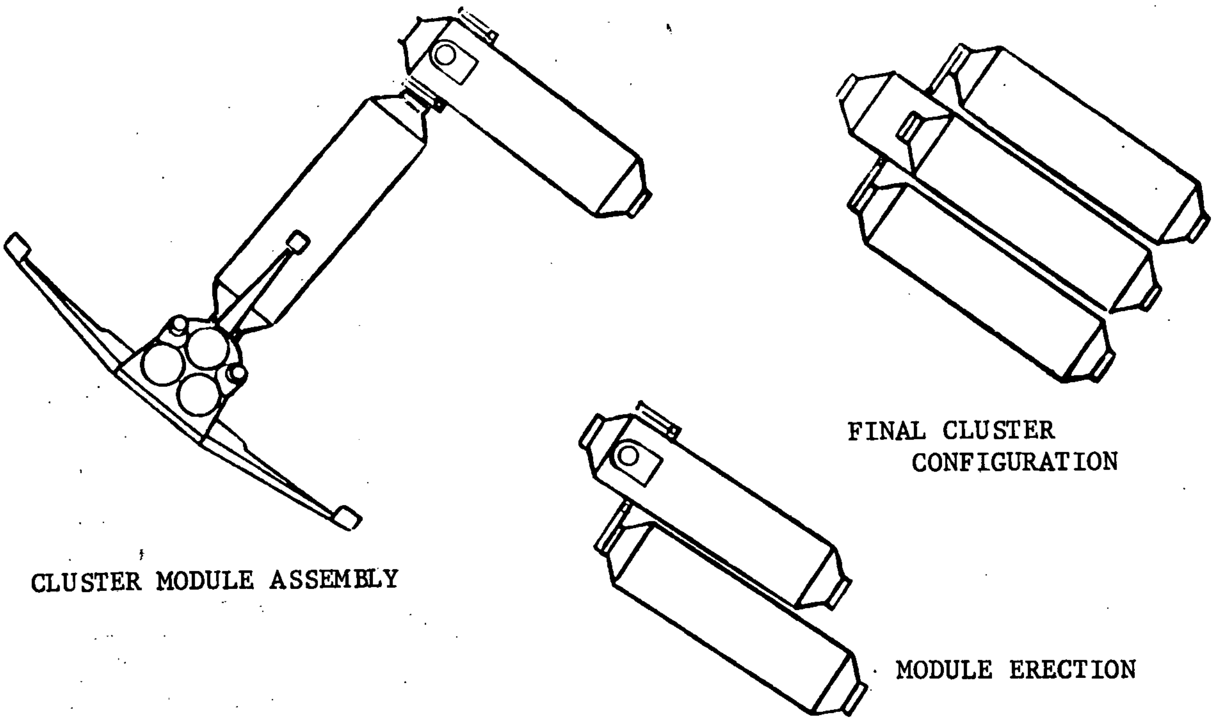
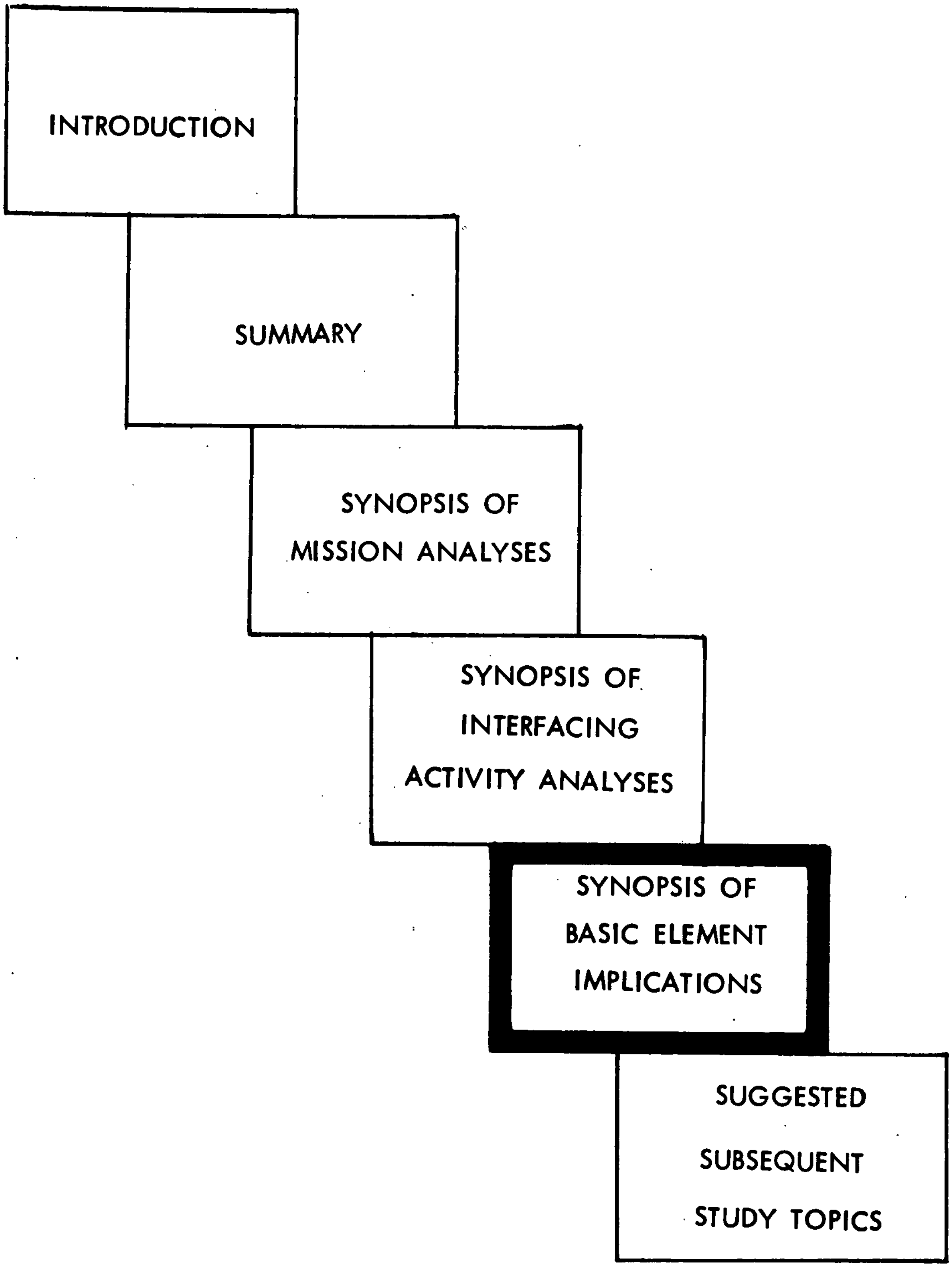


Figure 4-23. Center Core With Multiple Pivotal Docking Ports

The design influences resulting from the use of a CPS as a transport vehicle are dependent upon the thrust characteristics of its engines. If two fixed thrust engines (960K pounds total) are used, a complex assembly-load distribution mechanism is required. This requirement is not unique to the CPS, however. The LSB and resupply modules must be delivered in a disassembled configuration. The OLS and geosynchronous MSS may also be delivered in a disassembled configuration. Even if the RNS is used as the transport vehicle, a complex assembly/adapter mechanism is still required.

Options for control of the transport operation are the same as the alternate approaches for rendezvous. It is recommended that the EOS operate in an independent mode. CPS and RNS logistics elements should operate under the direction of ground control. Special tug missions will require independent operations, but in general the ground control approach is preferred.

Only safety critical or hazardous cargo conditions impose a requirement for a monitor and/or control interface between a logistics element and its attached payload. No payload operations were identified during the transport phase that would involve the logistics vehicle.


INTRODUCTION
SUMMARY
SYNOPSIS OF MISSION ANALYSES
SYNOPSIS OF INTERFACING ACTIVITY ANALYSES
SYNOPSIS OF BASIC ELEMENT IMPLICATIONS
SUGGESTED SUBSEQUENT STUDY TOPICS

5.0 SYNOPSIS OF BASIC ELEMENT IMPLICATIONS

Volume III of the technical report consists of an extraction and compilation of the analyses, recommendations, and design influence of the Orbital Operations study that pertain to four basic elements: the EOS orbiter, space tug, RAM, and MSS. The subsequent four tables (Tables 5-1, 5-2, 5-3, 5-4) summarize the more significant recommendations, hardware and operational considerations, and the interfacing activities that were the bases for the selections.

Development of both the pivotal mechanism approach and the manipulator approach is recommended for the EOS. Programmatic trades and updated traffic model analyses will be required to establish whether sequential or parallel development is preferred.

Proposed missions for unmanned tugs operating with other unmanned elements imposes the requirement for autonomous operations during close proximity operations primarily because of potential communication gaps and interruptions with remote control facilities.

The spectrum of RAM concepts operating in conjunction with the EOS is quite broad and varied. Thus, the recommendations reflect primarily an independent or modular dependent approach for support of RAMs associated with the EOS. RAMs associated with the MSS are dependent upon the MSS for almost all support.

MSS recommendations are indicative of the basic definition of this element; it is an orbital facility. As such the MSS requirements reflect long-term, autonomous operational capability.

Table 5-1. Major EOS Recommendations

Major Recommendations	Hdw & Oper'l Considerations	Interfacing Activities
1. Direct Automated Dock to all Elements Except Small Satellites - Manual Backup for Contingency	·Common Mating Port ·100-400 ft-lb Atten. ·$\leq$0.4 ft/sec Closing Velocity ·Scanning Laser Radar ·TV & Backup Aids	Mating Orbital Assembly
2. Jet Translation for Separation from Mated Elements	·EOS Active ·EOS Passive	Separation
3. Deploy, Retract, or Retrieve & Redeploy Single Payloads	·Pivot mechanism	EOS P/L Deploy EOS P/L Retract
4. Deploy/Retract Multiple Payloads on Same Mission & Mate with Small Satellites	·Manipulator ·Multiple Payload Attach Point Locations	EOS P/L Deploy EOS P/L Retract Mating Attach Elem Xport
5. Crew/Cargo Transfer to Payload in Cargo Bay & in Deployed Pos. - Shirtsleeve Prime Mode - IVA Backup Mode	·Flexible Tunnel ·Airlock ·41-in. dia Clear Opening	EOS P/L Deploy EOS P/L Retract Attach Elem Ops Crew Transfer Cargo Transfer
6. Direct EOS-to-Element and EOS-to-Ground Comm Links	·S-Band Equip & Omni ·VHF Equip & Omni	Communication Detached Elem Ops
7. Complete Autonomous Control for Rendezvous & Stationkeeping - Ground Control of EOS to within $\underset{\sim}{\sim}$50 n mi for Normal Missions	·Horizon Scanners & IMU ·Star Trackers ·Scanning Laser Radar ·VHF & S-Band Omni Antennas ·TV (for Inspection)	Rendezvous Stationkeeping Detached Elem Ops Communications
8. Deliver Large Quantity of Propellants to User Via Active Tank Module - EOS Stationkeeping During Subsequent Fluid Transfer	·OPD Not Required ·Tug Not Required ·Linear Acceleration Provided by Tank Module ·Att Control Provided by User Element	Propellant Xfer
9. Attached Elements have Access to Available EOS Subsystem Capabilities	·Comm (S-Band & VHF) ·Electrical Power ·Habitability ·Att Stab & Pointing	Attached Elem Ops

Table 5-2. Major Tug Recommendations

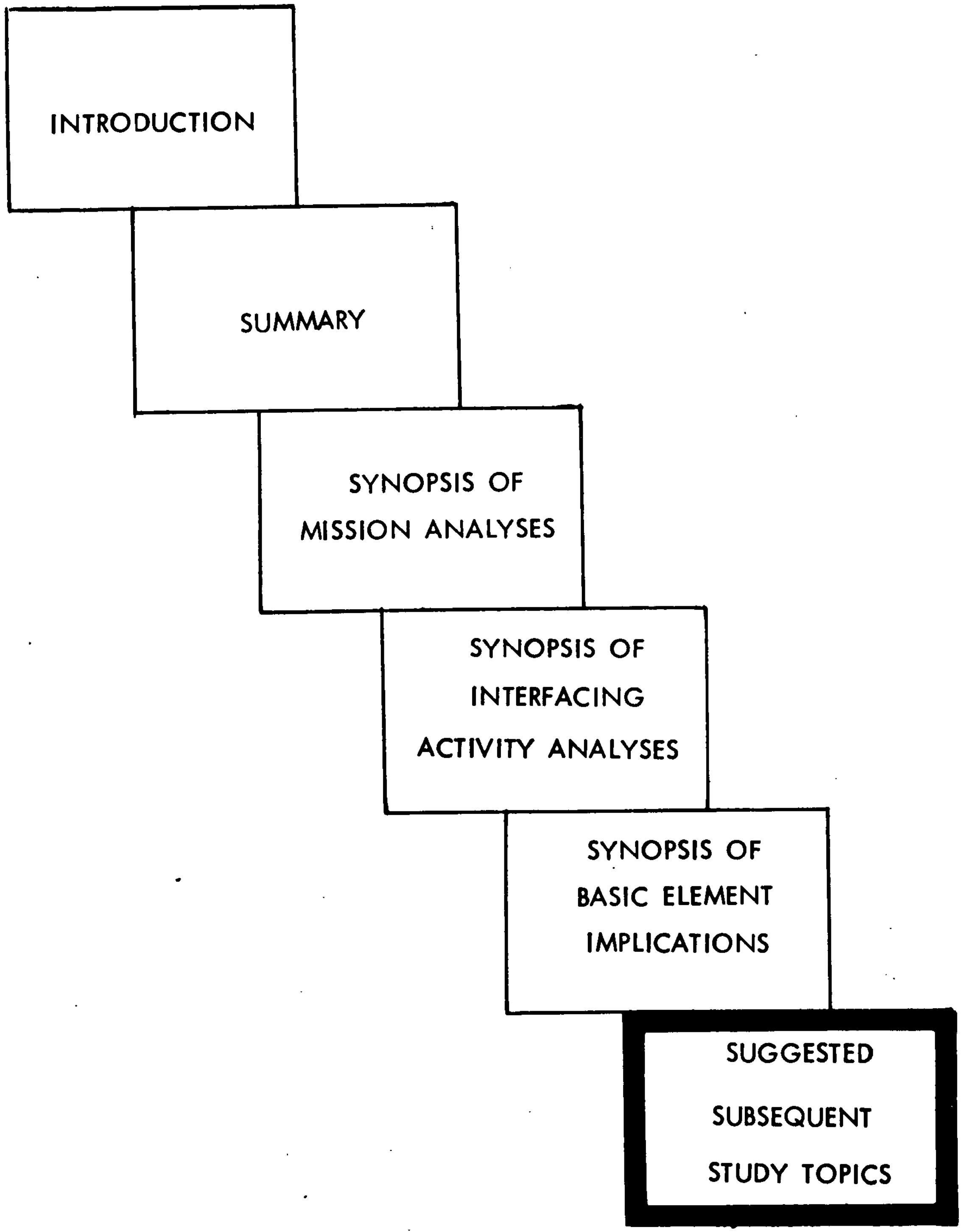
Major Recommendations	Hdw & Oper'l Considerations	Interfacing Activities
1. Direct Automated Dock to all Elements Except Small Satellites - Manual Backup for Contingency	·Common Mating Port ·100-400 ft-lb Atten. ·$\leq$0.4 ft/sec Closing Velocity ·Scanning Laser Radar ·TV & Backup Aids	Mating Attached Elem Xport
2. Mate with Small Satellites using Adapter	·Extention/Retraction Device	Mating
3. Jet Translation for Separation from Mated Elements	·TUG Active ·TUG Passive	Separation
4. Orbital Assembly to Payload Modules via EOS with Direct Dock Approach - Manipulator Assist where Reach is Practical	·Mating Ports at both Ends of all Modules ·Manipulator Attach Points	Orbital Assembly
5. Specialized EOS Payload Retention for all TUG's	·Hinge or Clamp Device to Retain TUG	EOS P/L Deploy EOS P/L Retract
6. Crew/Cargo Transfer between TUG and MSS or EOS - Shirtsleeve Prime Mode - IVA Backup Mode	·41 in. dia Clear Opening · ·Manually Unaided Cargo Transfer	Crew Transfer Cargo Transfer Attached Elem Ops
7. Direct TUG-to-Element & Direct TUG-to-Ground Comm Links	·S-Band Equip & Omni ·VHF Equip & Omni	Communications Detached Elem Ops
8. Autonomous Control for Stationkeeping of Manned TUG & Close Proximity Unmanned TUG - Ground Control of all TUG Rendezvous to within $\approx$50 nm for Normal Missions - Autonomous Control for Special "Fast Response" Unmanned Rendezvous	·Horiz Scanners & IMU ·Star Trackers ·Scanning Laser Radar ·VHF & S-Band Equip & Omni Antennas ·TV (for Inspection)	Rendezvous Stationkeeping Detached Elem Ops Communications
9. Transfer Large Quantity Propellants from Tank Mod via Fluid Transfer - EOS Stationkeeping during Operations	·Linear Acceleration provided by Tank Mod ·Att Control provided by TUG	Propellant Transfer

Table 5-3. Major RAM Recommendations

Major Recommendations	Hdw & Oper'l Considerations	Interfacing Activities
1. Direct Automated Dock DRAMS to MSS, EOS, & TUG	•Common Mating Port •100-400 ft-lb Atten. •<0.4 ft/sec Closing Velocity •Laser Reflectors	Mating
2. Jet Translation for Separation from MSS, EOS & TUG	•RAM Active •RAM Passive	Separation
3. ARAMS Added to MSS Via EOS W/Manipulator - Direct Dock Backup	•Manip Attach Points •Mating Ports at Both Ends	Orbital Assembly
4. Universal EOS/Payload Retention for All RAMS	•4 Point Coplaner Retention Concept (Except Pallets)	EOS P/L Deploy EOS P/L Retract Attached Elem Xport
5. Crew/Cargo Transfer to P/L in Cargo Bay & in Deployed Position - Shirtsleeve Prime Mode - IVA Backup Mode	•41-in. dia Clear Opening •Mechanically Aided Transfer Device	EOS P/L Deploy EOS P/L Retract Attach Elem Ops Crew Transfer Cargo Transfer
6. Direct RAM-to-Element, Direct RAM-to-Ground, & RAM-to-TDRSS Comm Links	•S-Band & Omni •VHF & Omni •Ku-Band & Directional Antenna	Communications Detached Elem Ops
7. Ground, EOS, and MSS Control of Rendezvous and Stationkeeping	•Laser Reflectors •S-Band Link •Star Tracker & Att Reference	Rendezvous Stationkeeping Detached Elem Ops
8. Transfer of Small Quantity Fluids & Gasses from EOS & MSS via Manual Plumbed Interconnect	•Shirtsleeve •Flex Lines & Quick Disconnects	Cargo Transfer
9. Attached RAMS have Access to Available EOS and Designated MSS Subsystem Capability	•Data Process & Storage •Electrical Power •Thermal & ECLSS •Communication •Att Stab & Pointing	Attached Elem Ops

Table 5-4. Major MSS Recommendations

Major Recommendations	Hdw & Oper'l Considerations	Interfacing Activities
1. Direct Automated Dock of all DRAMS & TUGS. Manipulator Berth of EOS, Cargo Mod, & ARAMS	•Common Mating Port •100-400 ft-lb Atten •$\leq$0.4 ft/sec Closing Velocity •Laser Reflectors •TV & Backup Aids	Mating
2. Jet Translation Separation by Mated Elements	•MSS Active •MSS Passive	Separation
3. Orbital Assembly by EOS W/ Manipulator - Direct Dock Backup	•Manip Attach Points •Mating Ports at both Ends of all Modules	Orbital Assembly
4. Universal EOS/Payload Retention for all MSS Modules	•4 Point Coplaner Retention Concept	EOS P/L Deploy EOS P/L Retract Attached Elem Xport
5. Crew/Cargo Transfer Between all MSS Modules and to Attached RAMS	•41-in. dia Clear Opening •Mechanically Aided Transfer Device	Crew Transfer Cargo Transfer Attached Elem Ops
6. Direct MSS-to-Element, Direct MSS-to-Ground, and MSS-to-TDRS Comm Links	•S-Band & Omni •VHF & Omni •Ku-Band & Directional Antenna	Communications Detached Elem Ops
7. Complete Autonomous Control for Rendezvous & Station-keeping of RAMS & Space TUG - Ground Control of EOS to within $\sim$50 n mi for Normal Missions	•Horizon Scanners & IMU •Star Trackers •Scanning Laser Radar •VHF & S-Band Omni Antennas •TV (for Inspection)	Rendezvous Stationkeeping Detached Elem Ops Communications
8. Transfer of Small Quantity Fluids & Gasses from Cargo Module via Manually Plumbed Connections	•Shirtsleeve •Flex Lines & Quick Disconnects	Cargo Transfer
9. Attached RAMS have Access to Designated MSS Subsystem Capability	•Data Process & Storage •Electrical Power •Thermal & ECLSS •Comm (S, VHF & Ku Band) •Att Stab & Pointing	Attached Elem Ops



SUGGESTED SUBSEQUENT STUDY TOPICS

6.0 SUGGESTED SUBSEQUENT STUDY TOPICS

During the course of the analyses of the Orbital Operations Study certain topics were identified as candidates for subsequent effort. A brief synopsis of the topics including the data base from this study and the potential benefits of the proposed studies are presented below.

ORBITAL OPERATIONS UPDATE

The usefulness of a body of data such as is contained in the Orbital Operations reports is very much a function of user understanding and acceptance, and in the applicability of the data to his current decision. Although the data is of a lasting, even generic nature, it is to some extent dependent upon the specific orbital traffic model and the specific characteristics of the various program elements involved. This would tend to limit the useful life of the reports to a year or two, because within any given year major changes will occur to at least one of the program elements and certainly to the orbital traffic model. Widespread knowledge of these changes will tend to make the user of the orbital operations data question the validity of the results. In view of this situation, the key recommendation for follow-on or future work is a periodic (or even continuing) formal effort to do the following tasks:

1. Work directly with potential users, particularly those who generate shuttle requirements, and make sure the data are known and understood and, if necessary, format the data as required to assist current element definition studies.

2. Revise the data and republish periodically, taking into account the results of current programmatic and vehicle studies and results of the ongoing EOS definition.

The first task could perhaps best be done by the NASA directly. The second task would be an annual contracted effort lasting approximately three months plus another month for document review and publication. The result would be to reassure the user of the validity of the data that did not change, and to supply new data reflecting the impact of recent programmatic or vehicle changes.

INTEGRATED DATA TRANSFER ANALYSIS

The Orbital Operations study was primarily concerned with element pair data transfer relationships. Only the MSS was identified as requiring multiple data transfer link capabilities. All other elements were limited to two links. However, up to 100 elements will be operating simultaneously in earth orbit by 1990. Almost all of these elements will require data transfer to ground-based users. This proliferation of data could result in saturation of any reasonable communication/data processing network unless integrated planning is accomplished.

The first major activity that is required is to analyze the types of data that will be generated and establish data compression techniques (e.g., skimming, sampling, change of state, etc.) that are practical for incorporation at the source--the orbiting element. Communication gaps, contact time duration, and/or multi-channel limitations of receiving stations will preclude transfer of raw data from so many elements.

The second major activity is associated with integrated mission planning. Tradeoffs between optimum and adequate orbits for the various elements must be conducted to determine if, by judicious placement in orbit, sharing of ground stations can be accomplished. Increasing orbital altitude will obviously increase station contact time. Proper phasing between elements will facilitate sharing of the ground facility. A detailed integrated analysis of the total spectrum of data transfer operations is required to determine if the proposed ground receiving facilities can cope with the transfer requirements of the proposed orbiting elements.

INCREMENTAL PROPELLANT RESUPPLY OF A SPACE TUG

Although the direct fluid transfer logistics option has been selected in this study as the preferred method for refueling of the CPS, RNS, and the tug, it cannot be categorically stated at this time that a propellant storage facility (either a mini-depot or another space-based tug) will not prove ultimately to be a desirable means for supporting a space-based tug. This type of facility has potential advantages from the standpoint of providing increased flexibility in mission planning pertaining to both EOS missions and tug missions. The EOS could possibly deliver full propellant loads on most propellant delivery missions, storing excess propellants on orbit. This would also permit greater flexibility in the selection of time at which tug refueling occurs and the amount of propellant transferred for each tug mission.

A synergistic operations (i.e., EOS utilization) advantage can be realized if EOS payload sharing can be utilized at appropriate intervals by delivering propellants to the storage facility when smaller payloads, such as satellites, are being delivered to the same orbit. In this way, full EOS payload capability might be attained on many more flights than would be possible without a storage facility in orbit.

A comprehensive trade study is recommended to investigate all of the important factors necessary to determine the cost effectiveness of on-orbit storage as compared to the use of dedicated EOS delivery flights. A detailed traffic model and cost estimates of alternate concepts, as well as their technical characteristics, will be major inputs to this recommended study. The major trades would be cost of the optimum propellant storage concept versus delta costs associated with utilization of EOS payload delivery capability with and without orbital propellant storage.

DOCKING PORT STANDARDIZATION

The analyses of the Orbital Operations Study indicated that standardization of a docking port for all orbital elements except small satellites was feasible. Four concepts were evaluated to sufficient depth to verify that an adequate design is practical. The large number of orbiting elements that are planned during the 1980's and will be required to dock to with each other makes it imperative that docking interfaces be standardized. A family of adapters comparable to the current effort to match the Apollo and the Russian spacecraft is unacceptable. Establishment of a standardized docking interface is rapidly becoming a critical item because of the iminent Phase C activities on the EOS orbiter.

SCANNING LASER RADAR DEVELOPMENT

In several interfacing activity analyses the use of the Scanning Laser Radar (SLR) was recommended. Admittedly it could not be established that an SLR was a requirement, but numerous operations could be greatly enhanced and safety margins significantly increased with the use of this device. SLR's are within the state-of-the-art. However, major development effort is required before space rated equipment is available. The development of an SLR will perhaps reap more synergistic benefits than any other singular device. The characteristic range and range rate accuracies of the SLR will permit more efficient and safer rendezvous operations, especially between unmanned elements. It is recommended that SLR development be implemented in the near future because, if elements are equipped with the device, some orbital operations and the corresponding equipment can be simplified (e.g., tracking equipment).

LIQUID-VAPOR INTERFACE CONTROL

The preferred concept for liquid-vapor interface control during in-space propellant transfer operations is linear acceleration. The proposed concept was to include jets on the propellant logistics module that would provide approximately 1×10^{-4} g's of acceleration continuously for the nominal fluid transfer period of 15 hours. The propellant is transferred during free-flying operations of the propellant module and the user vehicle (Tug, CPS, RNS). Attitude control is maintained by the user vehicle during the transfer operation.

Initial analyses indicate that a capillary transfer concept is feasible. It is recommended that an advanced technology study be initiated to define design concepts and, if practical, to develop hardware. With this concept, in-space propellant transfer could be accomplished with the user vehicle attached to the EOS. The logistics tank would not have to be separated from the EOS orbiter. Only initial propellant settling (ullage) would be required. Also the capillary concept would preclude the development of engines capable of thrusting continuously for 15 hours.